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AUTOMATION OF SLUDGE PROCESSING:
CONDITIONING, DEWATERING, AND INCINERATION

by

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16. ABSTRACT

This study developed and tested automated control strategies for municipal wastewater sludge processing. The strategies consisted of chemical conditioning vacuum filtration and incineration. The project was conducted at the St. Paul, Minnesota Metropolitan Waste Control Commission (MWCC) Seneca facility, a 24-mgd plant with parallel sludge processing trains.

Several strategies were developed for controlling lime and ferric chloride addition and filter cake production rate. Each strategy was evaluated during approximately 500 hours of operation. The performance of each strategy are summarized for variability and cost.

Automated strategies were developed for controlling incinerator hearth temperatures and air input. The strategies were designed to maintain the lowest possible furnace burning zone and minimize excess air. The test data show a substantial cost reduction for automated control.

On-line sensors were used to collect data and implement control strategies. Performance data for these sensors are summarized. A description of the digital data acquisition and control system is included.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxic Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researchers and the user community.

Many of our cities are faced with problems associated with the treatment and ultimate disposal of sludges produced by wastewater treatment processes. One of these problems is the operating cost of sludge treatment processes. This report describes a plant-scale study of automated control strategies discussed to optimize the operating cost of a sludge processing train. Strategies were developed for chemical conditioning, vacuum filtration, and incineration.

Francis T. Mayo
Director
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ABSTRACT

A plant-scale study developed and tested automated control strategies for a wastewater sludge processing train. The strategies were applied to three unit processes -- chemical conditioning (ferric chloride and lime), vacuum filtration, and incineration. The project was conducted at the St. Paul, Minnesota, Metropolitan Waste Control Commission (MWCC) Seneca facility, a 24-mgd plant using two parallel sludge processing trains.

Laboratory data based on analyses of 40 sample sets (raw, ferric-conditioned, and lime-conditioned sludges) indicated that the construction of a model to predict specific resistance was feasible. A total of 160 online data sets was collected over a 1-year period. Several models were subsequently developed and tested for controlling the dose of ferric chloride. The online data demonstrated that, for the local conditions, the only workable strategy for controlling lime dose was maintaining the pH $\geq$ 12.0.

Several strategies for controlling filter cake production rate were developed and evaluated during approximately 500 hr of operation. In addition, manual filter operation was monitored for approximately 2400 hr. Performance data are summarized for both control schemes in terms of process variability and cost.

Control strategies were evaluated for controlling the incinerator hearth temperatures and air input. The strategies were designed to maintain the burning zone as low as possible in the furnace and to minimize excess air. Data from two parallel tests demonstrate a moderate cost reduction using automated control.

A number of online sensors were installed to collect the necessary data required for developing and implementing the control strategies. Performance data are summarized for the sensors used. Also presented is a description of the digital data acquisition and control system designed and constructed for this project.

This report was submitted in fulfillment of Grant No. S803602 by the Metropolitan Waste Control Commission under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers the period July 1976 through June 1981 and work was completed as of September 1982.

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SECTION I

INTRODUCTION

A casual examination of the literature of the past 4 to 5 years demonstrates that when new wastewater treatment facilities are constructed and older facilities are upgraded, operating agencies as well as design engineers are putting more emphasis on process control. Several reasons for this increased emphasis are as follows:

1. Improving the reliability of treatment facilities in terms of meeting National Pollutant Discharge Elimination System (NPDES) effluent standards.
2. Improving treatment efficiencies and thereby minimizing the size and cost of capital projects.
3. Decreasing operating and maintenance costs by making more efficient use of energy, materials, and personnel.

The cost for solids handling and disposal at a conventional secondary treatment facility usually represents a substantial portion of the Operating and Maintenance (O & M) budget, 30% to 50%. Therefore the solids handling processes at one of the St. Paul, Minnesota Metropolitan Waste Control Commission (MWCC) treatment facilities were studied to determine the potential impact of improved process control. Process control can be accomplished by manual or automated means, but the complexity of the sludge dewatering and incineration processes limit manual control to the most elementary schemes. In addition, the interaction of the sludge handling processes along with the variable nature of the raw sludge requires a considerable degree of flexibility in the control system. Because of this, digital control techniques are preferred.

The purpose of the study described on the following pages was to develop and test on a plant scale several automated control strategies for a sludge processing train. The strategies consisted of chemical conditioning ($FeCl_3$ & $Ca(OH)_2$), vacuum filtration, and incineration. The work was conducted at MWCC's Seneca treatment facility during the period July, 1976 through June, 1981.

SECTION 2

SUMMARY AND CONCLUSIONS

A demonstration program was conducted at MWCC's Seneca Wastewater Treatment Plant to evaluate a number of automated control schemes for a sludge handling train consisting of chemical conditioning, vacuum filtration, and incineration. The overall objective of the project was to model and eventually control these three unit processes to obtain near optimum performance for any particular operating goal. Throughout the 5-year project period, both the control hardware and software were tested and evaluated using one of the plant's two sludge handling trains.

The data collected demonstrated that automation of both process trains at Seneca would yield annual savings substantially greater than $100,000 based on 1981 costs for sludge conditioning chemicals (ferric chloride and lime) and fuel. This conservative estimate of annual savings is based on the implementation of the following recommended control strategies:

1. The control of the chemical conditioning process consists of maintaining a $FeCl_3$ dose in the range of 6% to 12% (based on dry sludge solids) and adding sufficient lime to maintain a pH of 12.0.

2. The yield of the vacuum filter, in terms of wet weight per unit time, is controlled primarily by adjusting the drum rotational speed; however, to eliminate problems with thin cake, which does not discharge from the filter media readily, the vat level is adjusted to maintain a cake thick enough to discharge. The vat level is maintained at setpoint by varying the raw sludge flow rate, which in turn causes the chemical feed rates to change.

3. The furnace temperatures are maintained at approximately 540°C (1000°F) on hearth no. 2 and 950°C (1750°F) on hearth no. 4. These setpoint values are maintained by manipulating the burners on hearth nos. 3 and 5, respectively. The furnace pressure (hearth no. 1) is maintained in the range of -0.38 to -0.51 cm (-0.15 to -0.20 in.) by manipulating the induced-draft fan damper. All air not entering at the burners or through uncontrollable leaks is provided by recycled shaft cooling air. The flow of recycled cooling air is controlled to maintain a setpoint oxygen concentration in hearth no. 1.

Throughout the project, a number of field instruments were used to collect online data. The environment of the sludge processing train can be quite severe; thus it is not surprising that mixed reviews were obtained when the field instruments were evaluated. Most instruments were not specifically designed for sludge-related applications, and because of limits on both time and money, an exhaustive effort to make the instrument work was not always expended. In addition, no attempt was made to compare the various brands of instruments.

Based on the evaluation of the instruments used, the capability of the monitoring hardware was divided into three categories, as follows:

ACCEPTABLE	QUESTIONABLE	UNACCEPTABLE
pH	ORP	Viscosity
Solids	Oxygen	Cake thickness
Vacuum	Turbidity	Cake moisture
Cake weight		Tank level
Vat level		
Temperature		
Rotational speed		
Rotation position		
Sludge flow		

In addition, several concurrent studies were conducted at Seneca to determine whether commercially available online moisture analyzers could provide a continuous measure of cake moisture and solids. All of the instruments tested were considered unacceptable, as they failed to provide reliable estimates of cake moisture.

Even the acceptable monitors required significant maintenance effort. The extreme example is the conditioned sludge pH monitor, which required a rinse and cleaning at least once per 8-hour shift. Although the required frequency of maintenance for the other acceptable monitors was found to be lower, both the raw sludge solids monitor and the belt scale used to monitor cake production require frequent calibration to insure the success of the control system.

When process control schemes are developed for sludge-handling processes, both the hardware and software should be designed with flexibility in mind. Since it is highly unlikely that the sludge characteristics will remain constant for an extended period of time, the system should be designed to allow a limited number of operator-entered setpoints to maintain system operation without going to a complete manual mode of operation.

Because of the considerable interaction among the various sludge handling processes and the flexibility required, digital control techniques are preferred to the more conventional analog methods. Digital computers also provide the means for collecting and summarizing performance data in a cost-effective and timely manner. Performance summaries, such as the hourly, shift, and daily reports used in this project, can be valuable aids to plant managers when making decisions affecting sludge handling.

SECTION 3

RECOMMENDATIONS

A. SLUDGE CONDITIONING

1. Strategy

It was observed many times, prior to and during this study, that changes in the raw sludge characteristics have a dramatic impact on the performance of a vacuum filter and subsequently on the incinerator. Because of this, there is a natural tendency for operators to include a significant factor of safety when selecting pump speeds (doses) for feeding conditioning chemicals. The experience of this project demonstrated the need for an on-line method of identifying the dewatering characteristics of chemically conditioned sludge. It appears however that at the present time such a method is not available. In the absence of such a method the recommended control strategy is as follows.

$FeCl_3$--Maintain a constant dose, in terms of dry sludge solids, in the range of 6% to 12%. The choice of the setpoint is a function of the raw sludge variability and the operator time available to monitor filter operation. Since changes require little time it is recommended that the dose be maintained as low as possible.

Lime--Maintain a constant pH after lime addition. For stable operation at Seneca the setpoint should be 12.0.

2. Instrumentation

The implementation of the above strategies requires only three field instruments for measurement of raw sludge flow, raw sludge solids, and pH of the lime conditioned sludge. The instruments used were judged suitable for this application; however, other models (brands) may also be acceptable.

B. FILTRATION

1. Strategy

Because of the nature of the sludge processing trains at Seneca the recommended operating strategy is based on the assumption that the rate of sludge processing must be maximized. This is equivalent to maximizing the dry yield. Since a reliable, on-line, cake moisture analyzer was not found, the recommended strategy is based on maximizing the cake yield, in terms of wet weight, with the restriction that the capacity of the incinerator not be exceeded. The practical capacity of each incinerator falls in the range of approximately 5.4 to 6.4 wet mt/hr (6 to 7 wet ton/hr). After selecting this setpoint the recommended strategy is as follows:

Yield--The drum speed is adjusted to obtain the setpoint yield; however, in order to maintain a reasonable cake thickness, which ensures cake discharge, an upper limit of 18 RPH is applied. When the yield is below setpoint and the drum speed is below the upper limit, the drum speed will increase to increase yield. As the drum speed increases the cake thickness will decrease. In order to eliminate problems with thin cake, which does not discharge from the medium readily, equation [16], Section 10, is used to calculate a new vat level setpoint. The increased vat level will maintain a cake thick enough to discharge.

Vat Level--The vat level is maintained at setpoint by varying the raw sludge flow rate which, in turn, causes the feed rate of $FeCl_3$ to vary.

In order to implement this strategy the operator must enter the setpoint value for yield along with the constants K_9 and K_{10} from equation [17].

2. Instrumentation

Once the conditioning strategy is adopted, the implementation of the filter strategy requires only three additional field measurements as follows: a belt scale to determine cake yield, a level detector to measure vat level, and a tachometer to determine the rotational speed of the filter drum. The instruments used during this study were found to be acceptable; however, it should be pointed out that all belt scales used in this application will require considerable maintenance effort to maintain calibration.

C. INCINERATION

1. Strategy

The recommended control strategy is based on the evaluation of the Seneca incinerators summarized in Section 12.D along with the testing conducted in June of 1981. The strategy is divided into two areas as follows:

Temperature--Only the burners on hearths no. 3 and 5 are used in this strategy. The hearth 3 burners are operated to maintain a temperature of approximately 540°C (1000°F) on hearth no. 2; and the burners on hearth 5 are controlled to maintain a temperature of approximately 950°C (1750°F) on hearth no. 4. For the typical loading rates observed at Seneca these setpoints result in hearth 4 as the main burning hearth.

Air Flow--The air flow strategy consists of maintaining the furnace pressure in the range of -0.38 to -0.51 cm (-0.15 to -.20 in) H_2O. For cake loadings below approximately 4.1 wet mt/hr (4.5 wet ton/hr) the lower (absolute value) setpoint is sufficient. A lower limit of approximately 20% open should be established for the induced draft damper. This will prevent problems associated with low draft values. The atmospheric air damper should remain closed; and, all air not entering at the burners or through uncontrollable leaks should be provided as recycled shaft cooling air. The flow of recycled cooling air should be controlled to maintain the desired O_2 concentration on hearth no. 1. The O_2 setpoint should be determined from visual observation on hearths 1-4. Sufficient O_2 should be provided to minimize smoke generation.

During the test, it appeared that air may have entered through the sludge feed drop gate at the top of the incinerator. For this reason it is recommended that the O_2 concentration be determined on hearth no. 1 as opposed to the downstream location used during the tests.

It is also recommended that a continuous measurement of opacity be used to provide a feedback to adjust the oxygen setpoint and/or filter yield.

2. Instrumentation

This strategy would utilize the standard temperature and pressure sensors found on most furnaces. In addition to these instruments an oxygen analyzer is required on hearth no. 1. An in situ type analyzer can be used if it is constructed of materials not subject to corrosion; however, an analyzer located outside the furnace, but which samples continuously, may be better both in terms of reliability and maintenance costs. MWCC has no recent experience with continuous opacity measurements; however, it appears that such instruments are available.

D. SENECA

Because of the substantial quantity of liquid sludge hauled to Seneca for processing (Section 4.A.) the two dewatering trains have been operating near their practical capacity for several years. Studies were initiated in 1977 to expand the dewatering capacity. A third vacuum filter was initially considered; however, because of the relatively high cost for conditioning chemicals and the low volatile content of the cake produced, centrifuges and belt presses were also considered. After a considerable amount of onsite testing a performance specification was prepared which included both centrifuges and belt presses. A contract was awarded early in 1980 for one belt press. The installation contract was awarded early in 1982; and, it is anticipated that the unit will be operational in 1983.

Although a request was submitted to extend the project period without additional funds, the project period ended April 30, 1981. When the disc drive on the computer failed early in July, 1981, the decision was made not to make the repairs, estimated to cost $1400, until the final disposition of the control hardware, partially purchased with grant funds, was determined. A verbal committment was obtained from EPA early in November, 1981 to waive title to the items requested by MWCC. At that time the decision was made to spend approximately $10,000 to conduct the following tasks:

Item	Task	Estimate
1.	replace disc drive	$1400
2.	debug software	2000
3.	prepare as-built documentation	1200
4.	revise control software manual	1200
5.	check all I/O channels, calibrate	500
6.	prepare operators manual	1200
7.	modify/consolidate software	1200
8.	operator training	1200

The purpose of the above modifications was to provide a reliable operator oriented control system. The installation of the new belt press however prevented use of the control system because of major modifications to the control room in the solids building. Both of the remote terminals had to be moved which required major wiring changes. It is anticipated however that train no. 1 solids processing equipment will be under computer control in 1983. In addition, it is anticipated that the polymer feed system for the belt press and incinerator No. 2 will be included in the control scheme.

As part of the ongoing modification at Seneca, contracts have been awarded to install oxygen analyzers and opacity monitors on both incinerators. The oxygen analyzers will be of the same general type used in this project but will be constructed of Hastelloy to minimize corrosion problems. The oxygen analyzer will not, however, be located in the furnace as recommended because of concern about temperature excursions and potential damage to the sensing elements.

E. FUTURE WORK

A major effort of this project was dedicated to characterizing the dewaterability of sludge using on-line measurements. If the chemical conditioning scheme used at Seneca ($FeCl_3$ and $Ca(OH)_2$) is to be operated in an efficient manner timely characterization is required. MWCC is aware of at least one instrument manufacturer that has been trying to construct an automated method for determining specific resistance. Because of the potential for obtaining real control of the chemical conditioning process a substantial effort, in terms of further research, is justified in this area.

One of the goals of process control, manual or automated, is to maintain a high degree of process efficiency. For a dewatering process, efficiency is, at least partially, determined from the cake solids content. In like manner the efficiency of incineration is determined from the water and solids loading to the furnace. At the present time these process efficiencies cannot be determined in a timely manner but only well after the fact. The optimization of any sludge dewatering and/or incineration process is dependent on reliable and timely solids or moisture data. It is recommended that all methods of on-line moisture determination be evaluated periodically and that the results of these tests be distributed to the industry in a timely fashion.

SECTION 4

FACILITY DESCRIPTION

A. GENERAL

The Metropolitan Waste Control Commission (MWCC), which was formed in 1970, currently operates 14 wastewater treatment plants in the Minneapolis-St. Paul metropolitan area. Average flows at the facilities fall in the range of approximately 760 to 760,000 m^3/d (0.2 to 200 mgd). All of the work described in the following sections was conducted at the Seneca Wastewater Treatment Plant which is located on the Minnesota River in the City of Eagan, Minnesota. This facility serves a number of suburban communities south of Minneapolis.

The Seneca Facility was placed in operation in July, 1972 with an average design capacity of 90,840 m^3/d (24 mgd). During 1980 the flow averaged approximately 49,200 m^3/d (13 mgd). Based on MWCC records approximately 10% of the influent flow is from industrial sources. The treatment scheme consists of screening, grit removal, primary sedimentation, complete mix activated sludge, final sedimentation, and chlorination prior to discharge to the receiving stream.

B. LIQUID TRAIN

The liquid treatment portion of the plant is divided into two parallel treatment trains, as illustrated in Figure 1, each with a nominal capacity of 45,420 m^3/d (12 mgd). The following paragraphs describe one of the parallel treatment trains; however, considerable flexibility does exist and the flows can cross over between trains at several points.

The raw wastewater is screened to remove large debris which might interfere with mechanical equipment downstream. Grit is removed in an aerated grit chamber with a detention time of approximately 15 minutes.

Subsequent to grit removal the wastewater flows by gravity to the primary sedimentation basin. The basin is square and has a side wall depth of 3.66 m (12 ft). The surface overflow rate at design flow is 20.86 m/d (512 gpd/sq ft). The basin is equipped with a center inlet and sludge plows for central sludge withdrawal. Surface skimming equipment is provided for removal of scum.

The primary effluent is distributed by gravity to two mechanically aerated basins each with a volume of approximately 2,763 m^3 (730,000 gal). Total

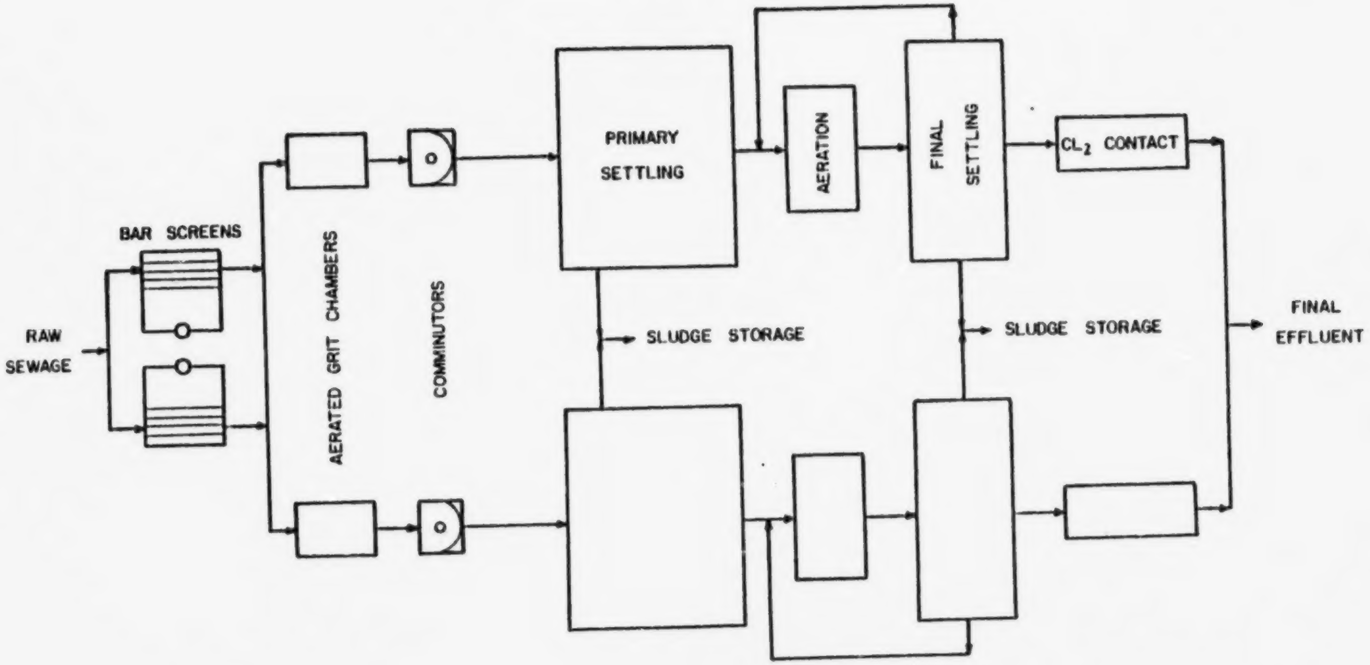


Figure 1. Flow diagram for Seneca liquid processing.

aeration time at design flow, excluding sludge recycle, is approximately 3 hours. The dissolved oxygen concentration in the basin is adjusted by controlling the aerator submergence with adjustable weirs. The mixed liquor discharges to two square final sedimentation basins with side wall depths of 4.57 m (15 ft). The surface overflow rate at design flow is 19.96 m/d (490 gpd/sq ft). These basins utilize center inlets and skimming equipment similar to the primary basins; however, the sludge collector is of the "vacuum cleaner" type. Both variable and fixed speed pumps are used to return and waste sludge as required. Excess sludge is wasted to floatation thickeners.

The plant effluent is disinfected with chlorine prior to discharge to the receiving stream. The chlorine contact chamber provides a nominal retention time of 22 minutes at design flow prior to discharge through approximately 0.8 km (0.5 mile) of 2.13 m (84 in) diameter outfall sewer.

The discharge permit granted by the State of Minnesota requires that the Seneca plant meet the following effluent requirements on a monthly average basis.

Suspended Solids - 30 mg/l
BOD - 25 mg/l
Fecal Coliform - 200/100 ml (geometric mean)

During 1980 the average effluent concentrations were:

Suspended Solids - 16 mg/l
BOD - 16 mg/l
Fecal Coliform - 12/100 ml (average of monthly geometric means)

C. SLUDGE TRAIN

1. General

The solids processing operations are housed in the Seneca solids processing building and include floatation thickening of waste activated sludge, vacuum filtration and incineration. All of the primary and waste activated sludges generated in the Seneca liquid treatment trains are processed along with sludges hauled to Seneca from other MWCC facilities. During 1980 approximately 215,745 m^3 (57 mil gal) of liquid sludge were processed including approximately 93,490 m^3 (24.7 mil gal) which were hauled to the plant. The major portion of this foreign sludge was generated at MWCC's Blue Lake facility which is located on the Minnesota River approximately 24 km (15 mile) upstream of Seneca. Blue Lake is an activated sludge facility, approximately the same size and age as Seneca, but without sludge processing facilities. Approximately 11% of the Blue Lake influent is from industrial sources.

The schematic diagram presented in Figure 2 describes the sludge dewatering trains. Each of the two parallel treatment trains consists of chemical conditioning facilities, one vacuum filter and one incinerator. The two trains can be cross connected just upstream of the incinerators. The ash from

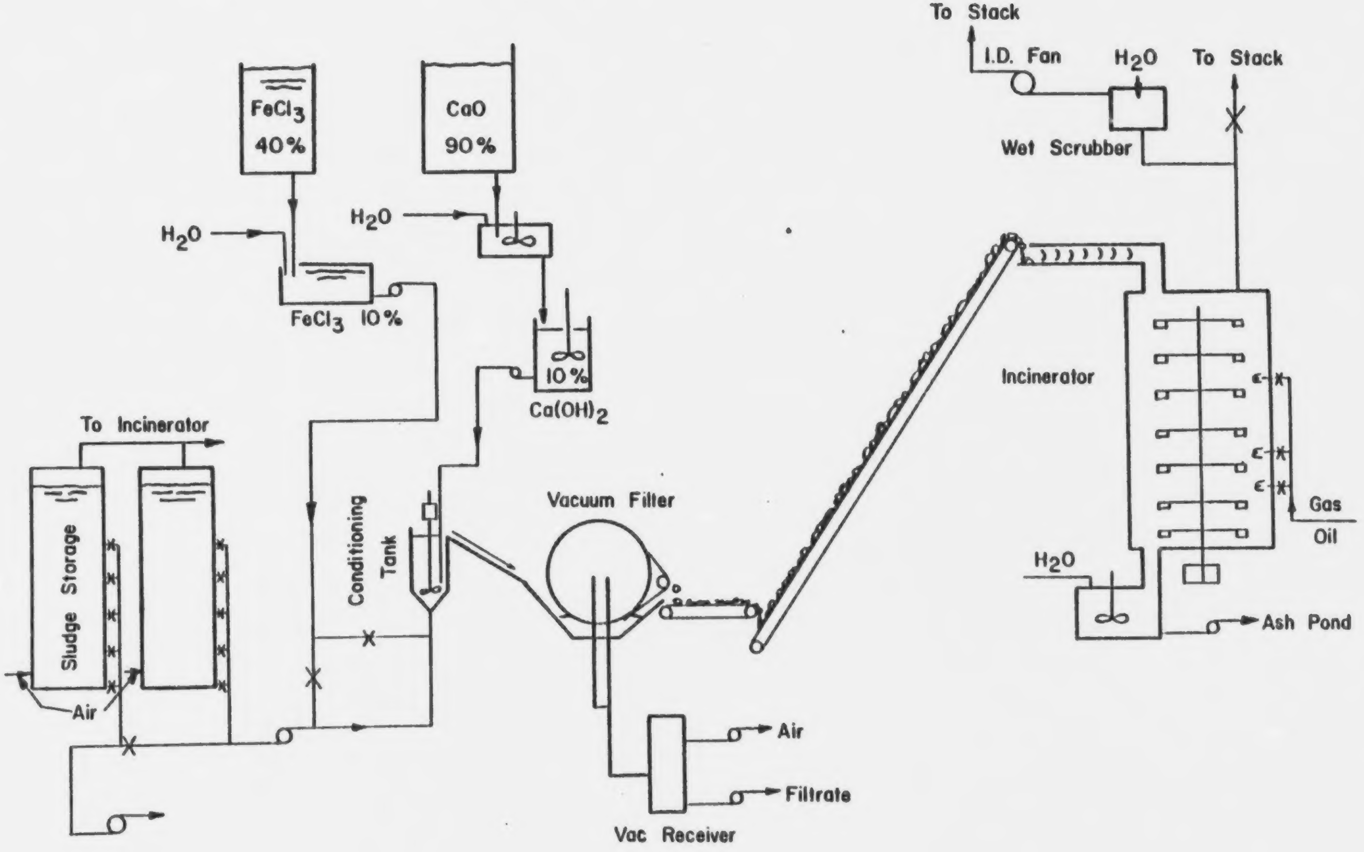


Figure 2. Flow diagram for Seneca sludge processing.

each incinerator is slurried and transported to a lagoon for gravity dewatering and storage prior to landfilling.

2. Storage

The primary sludge and air floatation thickened waste activated sludge, along with the hauled sludges, are discharged to two holding tanks. The tanks are 12.2 m (40 ft) deep and have a combined capacity of approximately 2,328 m^3 (615,000 gal). The contents of the tanks may be mixed by introducing air near the bottom on a timed or manual basis. The mixing air is vented to the incinerators to prevent odor problems.

Sludge can be withdrawn from the tanks at seven points along the side wall between 0 and 10.7 m (35 ft) above the tank floor. In addition, supernatant removal is provided with the supernatant returned to the primary influent. The sludge is removed from the storage tanks using positive displacement pumps of the progressing cavity type and transported to the conditioning tank through approximately 46 m (150 feet) of 15.2 cm (6 in) diameter pipe.

3. Chemical Conditioning

Ferric chloride and lime are used to condition the sludge prior to dewatering. Ferric chloride is delivered to the facility in solution form at a nominal concentration of 40% $FeCl_3$. The concentrated solution is diluted to approximately 10% $FeCl_3$ in a 7.57 m^3 (2,000 gal) day tank. Air operated diaphram pumps are used to transport the diluted $FeCl_3$ solution to the point of addition to the sludge. Prior to the initiation of this study the $FeCl_3$ was added to the sludge at the base of the conditioning tank. The point of addition was changed to allow for some additional mixing prior to lime addition. The current addition point is approximately 7.6 m (25 ft) downstream of the sludge pump and approximately 38 m (125 ft) upstream of the conditioning tank.

Lime is delivered to Seneca by railcar and stored in a large silo. The delivered material is approximately 90% CaO by weight. The CaO is converted to $Ca(OH)_2$ using standard slaking apparatus. The $Ca(OH)_2$ slurry is maintained at approximately 10% CaO by weight and is transported to day tanks by gravity. Positive displacement pumps, of the progressing cavity type, are used to transport the lime slurry to the conditioning tank.

The conditioning tank has a volume of approximately 0.76 m^3 (200 gal) and is equipped with a variable speed mixer. The mixing impeller consists of 3 vertical, triangular shaped blades and rotates in the range of 25 to 84 RPM. The conditioned sludge discharges from the tank over a weir approximately 40.6 cm (16 in) long and flows down an inclined pan to the filter vat.

4. Vacuum Filtration

A conventional rotary drum filter, manufactured by Dorr-Oliver, is used to dewater the conditioned sludge. The drum is 3.66 m (12 ft) in diameter and has a total area of 49 m^2 (528 sq ft). The drum is covered with polyethylene media and can be rotated in the range of 9 to 30 RPH.

The filter vat is equipped with a variable speed, paddle type agitator which can be operated in the range of 5.7 to 13 cycles per min.

The vacuum system is common to both the form and drying zones of the filter. Under the normal operating conditions, a vacuum of 51 to 64 cm (20 to 25 in) Hg can be maintained in the form zone; however, if cracks develop in the drying zone, the form vacuum drops substantially.

The cake discharges from the filter media by gravity and falls onto a horizontal conveyor belt, which in turn, discharges to the inclined conveyor used to load the incinerator.

5. Incineration

The filter cake is discharged from the inclined conveyor to a screw conveyor which subsequently discharges to the 7 m (23 ft) diameter, seven hearth incinerator through a hinged drop gate. The incinerator has a rated capacity of 6.35 mt/hr (7 ton/hr) at 22% solids. Burners are located on hearths no. 3, 5, and 6 to provide the energy to maintain combustion temperatures. The burners can be fueled with natural gas or fuel oil.

The cake and ash are moved from hearth to hearth by a series of rakes or plows attached to rabble arms which rotate around a central shaft. The rotational speed of the rabble arm drive can be adjusted in the range of 0 to 2 RPM.

Ash is discharged from the bottom hearth into a slurry tank. The ash slurry is then pumped to an ash pond for intermediate storage. Ash balls which consist of volatile sludge solids covered and insulated by char are removed on a bar screen just above the slurry tank.

Combustion air is supplied from several sources. Air is metered into the furnace at each burner to ensure complete combustion of the fuel. The induced draft fan maintains a slight negative pressure in the furnace; thus, air will be pulled into the furnace at all openings. An atmospheric air damper is located on hearth no. 7 to provide combustion and cooling air. Significant quantities of air may also enter at the ash slurry chute as well as observation holes that may be left open. The rabble arm shaft cooling air can be returned to the furnace or discharged directly to the stack.

The hot gases, soot and fly ash discharged from the furnace are ducted to a wet plate impingement type scrubber and subsequently discharged to the stack.

SECTION 5

OPERATION CONSIDERATIONS FOR SLUDGE TRAIN

A. GENERAL

Prior to 1970 most of the small treatment facilities in the Minneapolis-St. Paul metropolitan area disposed of their sludges on land. As the metropolitan area expanded and environmental legislation turned more restrictive it became increasingly difficult to obtain land, and permits, for disposal of the increasing volumes of sludge. Although MWCC is aggressively pursuing a land disposal program with approximately 182,000 mt (200,000 tons) hauled to farms in 1981, incineration and land disposal of ash will be the major sludge disposal scheme in the forseeable future.

The Seneca liquid trains are currently operated at approximately 50% of design capacity; however, because of the significant quantity of sludge hauled from other plants, the sludge processing trains are operated at their practical capacity. Under these circumstances the goal set for the sludge processing trains is to process the maximum volume of liquid sludge. That portion of the Blue Lake sludge which cannot be processed at Seneca must be hauled to MWCC's Metropolitan facility for dewatering and incineration. The additional haul distance, approximately 24 km (15 mile) one way, substantially increases the cost of sludge processing. The Blue Lake sludge cannot be used on farm land because it has not been stabilized.

B. SLUDGE PROCESSING LIMITATIONS

1. Chemical Conditioning

Each of the two sludge processing trains at Seneca consists of three processes in series - chemical conditioning, vacuum filtration and incineration. Depending on circumstances, any one of the three processes can be the rate limiting step.

Prior to the initiation of this project the filter operator had no quantitative criteria on which to judge the effectiveness of chemical conditioning. If the cake discharged from the filter cloth and a reasonable cake production rate was maintained the sludge was judged to be adequately conditioned. If problems were encountered with the cake discharge or production rate, changes were made in the ferric chloride and/or lime dose. Each operator's response was based largely on his previous experience. In terms of meeting the plants performance goal the natural tendency was to overdose.

Because sludges from several plants were/are being processed at Seneca, problems were encountered even when the chemical feed rates were extremely high. As the physical and chemical characteristics of the raw sludge change, the dewatering characteristics of the conditioned sludge may change significantly even when overdosed. Rapid changes prevent both the filtration and incineration processes from maintaining steady state conditions. The operators have observed that old sludges are much more difficult to condition than fresh sludges; however, if the inventory in the sludge holding tank is maintained at a minimum, the impact of batch discharges from other plants on sludge properties is increased.

Because of the nature of the material used for conditioning, the chemical feed pumps fail periodically. The impurities in the lime accelerate the wear of both the stator and rotor of the progressive cavity pumps. Impurities in the ferric chloride may prevent the check values from sealing properly which allows back flow. When the sludge is overdosed significantly it is difficult to recognize the gradual deterioration of pump performance and acute failures are more likely to occur. When one of the pumps fails, the operator most likely will not become aware of this fact until the cake does not discharge from the cloth and pump speed adjustments do not alleviate the problem. Such failures require a full shut down of the filter and incinerator until another pump is put into service, the filter vat and conditioning tank must be purged of the poorly conditioned sludge, and the filter cloth must be cleaned.

As the subsequent chapters will point out in detail, many of the problems related to chemical conditioning can be ameliorated by monitoring the physical and chemical characteristics of the raw and conditioned sludges.

2. Vacuum Filtration

Prior to the initiation of this study the vat level was not automatically controlled on either of the filters. The operator thus had four options to change the cake yield: (1) change drum speed, (2) change vacuum, (3) change sludge pumping rate, and (4) change chemical conditioning. As a practical matter the vacuum is held at the maximum value at all times. If the sludge is overdosed moderate changes in chemical feed rates do not affect a significant change in dewatering characteristics. The four options were thus reduced to changes in the drum speed and/or pumping rate. Change in drum speed generally required a change in sludge pumping rate. After several revolutions the vat level reaches a new equilibrium. Small step changes are required to ensure that the vat does not overflow or go so low as to expose the form zone on the filter. Because of the lack of simple automated control and the uncertain nature of the manual control scheme available, it is unlikely the operating goal was attained a significant portion of the time.

Because of the variable nature of the raw sludge, the conditioning process, and filter operation itself, it is extremely difficult for an operator to maintain a steady output of cake with uniform burning characteristics. The data presented in Figure 3 were collected during a 24-hour period in 1975. The solids content of the cake varied from 14% to 25.5% and the volatile solids content fell in the approximate range of 53% to 68%. For a six-hour period the sludge was returned to the plant's influent structure

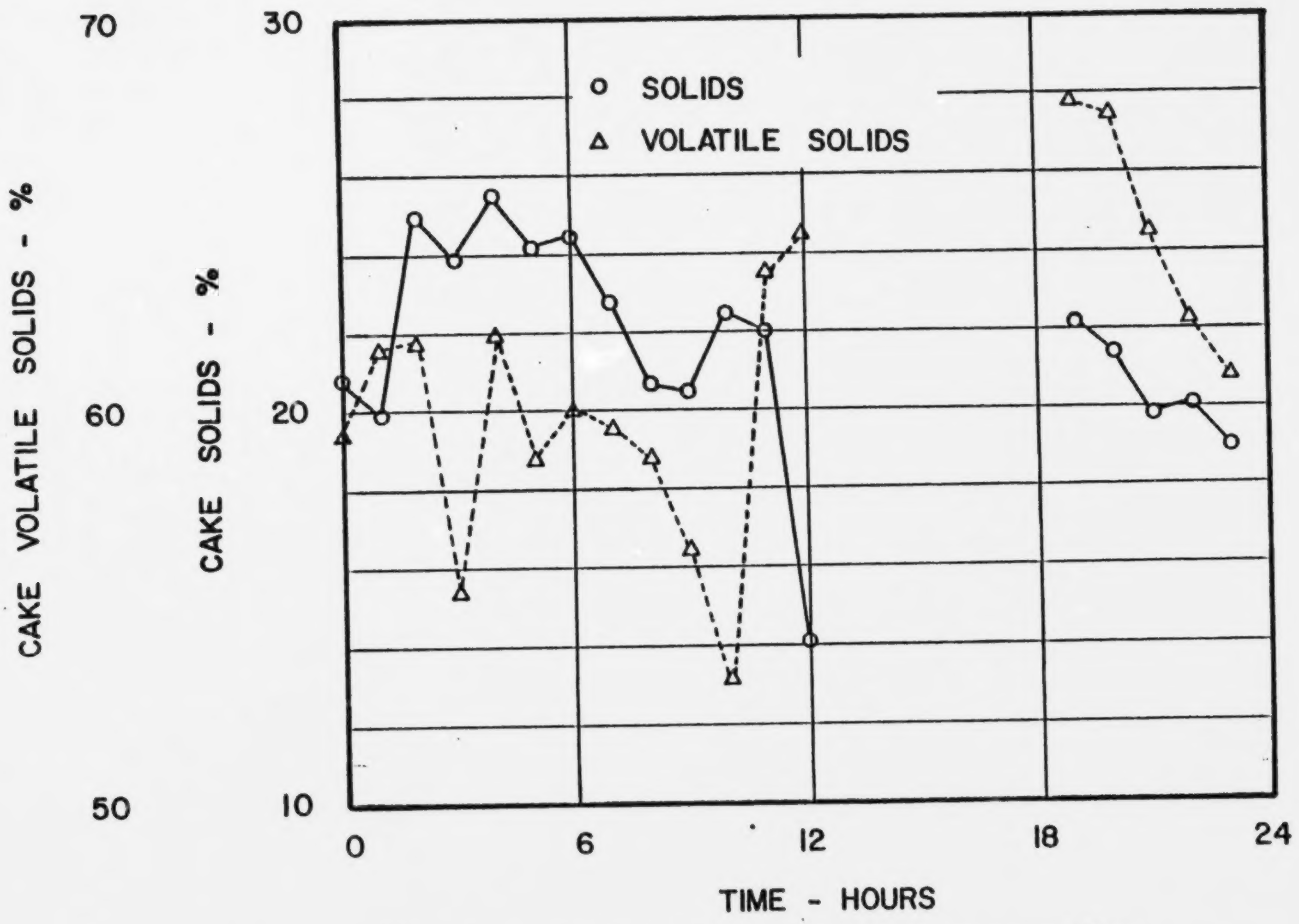


Figure 3. Variability of cake produced during manual control of vacuum filter.

because a cake which would discharge from the filter cloth could not be formed. During a similar sampling period in 1976 the solids content varied in the range of approximately 20% to 28% and the filter yield varied by a factor of three.

Experience with the sludges processed at Seneca indicates that the pH of the conditioned sludge must be raised to approximately 12.0 to obtain adequate dewatering characteristics. At this high pH there is a definite tendency to deposit lime on all surfaces including the filter cloth and vacuum system. When the sludge is overdosed it is reasonable to believe that this plating tendency increases thus causing increased downtime for acid cleaning.

Prior to and throughout the demonstration project, the capacity of the vacuum filters was limited by the vacuum system. Because the filtrate pumps do not have sufficient capacity to dewater the vacuum receiver, Figure 2, filtrate passes through the vacuum pumps. This causes excessive wear and has decreased air handling capacity significantly. New vacuum pumps were installed in the fall of 1979. The pumps are routinely acid cleaned twice a year; however, during 1980 they were taken out of service approximately twice per month to rectify various problems.

3. Incineration

Because there is no cake storage capacity at Seneca, the incinerator in each train must burn the cake as produced. This must be accomplished within the constraints of meeting air pollution standards and maintaining hearth temperatures below 1100°C (2000°F) to protect the furnace structure. In addition, it is required that good volatile destruction be obtained and the formation of ash balls be minimized.

Because of the variable nature of the filter output it is extremely difficult to maintain steady burning conditions in the incinerator. The situation is further complicated by the fact that the analog temperature control system, designed to control the burners, does not function properly because of interaction between the hearths. In addition, the excess oxygen level is not measured and therefore cannot be easily controlled.

In the existing system the operators have few tools available to them to attain the operating goal and must make judgements based on past experience and process understanding. It is thus not surprising to find that the performance of the entire sludge processing train can and does vary from shift to shift.

The piping system used to transport ash slurry from the incinerator to the ash lagoon, a distance of approximately 0.65 km (0.4 mile) is the weakest link in the process chain. When this line plugs, all sludge processing down stream of the sludge storage tanks terminates. During the project this failure occured approximately 10 times per year; and, each occurrence resulted in approximately 3 to 4 days of downtime.

C. COST

The total operating cost for sludge dewatering at Seneca is the sum of the costs for chemicals, energy, and labor. The operating records for the 5-year period 1976 through 1980 indicate that approximately 41,700 mt (46,000 tons) of sludge solids (dry weight) were dewatered and incinerated. Because the belt scales are unreliable unless calibrated regularly, the estimate of sludge solids is based on sludge flow measurements and solid analysis. The average chemical conditioning requirements on a sludge solids basis were 7.74% $FeCl_3$ and 29.8% CaO. Based on MWCC chemical supply contracts in force during the summer of 1981 the cost for conditioning chemicals is as follows:

Material	Ave. Dose %	Chemical - $/mt	($/ton) Sludge Solids
$FeCl_3$	7.74	19.01	($17.24)
CaO	29.8	29.33	($26.60)
Total	--	48.34	($43.84)

Natural gas is supplied to Seneca on an interruptable basis. As the system wide demand for gas increases during the cold weather months the gas supply is terminated and fuel oil must be used in the incinerators. During the 1978-80 period fuel consumption, on a dry sludge solids basis, averaged 54.75 l/mt (13.12 gal/ton) for fuel oil and 355.7 m^3/mt (11,400 cu ft/ton) for natural gas. The average fuel costs based on 1981 unit costs are as follows:

Material	Fuel Cost - $/mt	($/ton) Sludge Solids
Fuel Oil (No. 2)	14.47	($13.12)
Natural gas	33.43	($30.32)
Total	47.90	($43.44)

A total of five positions are involved in the operation of the solids building as follows:

Position		% Time	1981 Cost - All Shifts (including benefits)
Bldg. Oper.	(Foreman)	90	$128,600
Asst. Oper.	(Filter)	100	133,057
Asst. Oper.	(Incinerator)	100	133,057
Oper. Atten.	(Laborer)	100	128,338
Oper. Atten.	(Laborer)	50	64,169
TOTAL			$587,221

The operating labor cost, for the average processing rate of 8,350 mt/yr (9,210 ton/yr) sludge solids, based on 1981 salaries and benefits averages $70.30/mt ($63.76/ton). Only those labor costs which are easily estimated and allocated to the solids processing trains are presented above. Plant supervision, engineering, and maintenance costs (by contract or MWCC tradesmen) are not included.

For those cost categories considered, the summation of dewatering and incineration costs total approximately $166/mt ($151/ton). Based on the average processing rate at Seneca, the above costs account for 47% of the total operating budget for 1981.

SECTION 6

PROJECT OBJECTIVES

A. GENERAL

During the past ten years the MWCC has finished construction of four new wastewater treatment facilities and has made major modifications to other facilities. These changes were made to increase treatment efficiencies and thus provide improved effluent quality. As a result of the changes, however, the treatment facilities became much more complex. It has been observed that as the complexity of treatment processes increase it becomes more difficult to optimize their performance. This occurs for several reasons including the changing wastewater characteristics and the variation in the skill and quality of judgement of operating personnel every eight hours. Failure to maintain optimum control of any of the several unit processes may degrade effluent quality and lead to waste of energy and dollars, both in short supply.

The data presented in Section 4 demonstrate that the operating cost for sludge dewatering and incineration at MWCC's Seneca facility amount to slightly less than 50% of the plant's operating and maintenance budget. If maintenance costs for dewatering and incineration along with the cost of ash disposal are considered the sum is well over 50% of the plant's annual operating and maintenance budget. Because of the high operating cost and the variable level of performance (See Figure 3) the decision was made to investigate the potential for cost reduction through process automation.

Although the specific objectives changed throughout the project period, the overall objective was to model and eventually control the three unit processes, sludge conditioning, dewatering, and incineration, so as to obtain near optimum performance for a particular operating goal. This goal may vary from maximizing the volume of liquid sludge processed to maintaining specified limits for particulates in the stack discharge and will change throughout a years time. It was reasoned that if adequate models could be generated, and preliminary data indicated this was possible, it would be relatively easy to prepare an algorithm designed to minimize total cost for any given operating scheme.

As is often the case, the project staff was too optimistic when estimating the resources required to obtain the stated objective. In addition the constraint of conducting the project at an operatng facility running at near capacity may have been underestimated. As a result of these factors the overall objective was not attained; however, it was demonstrated that considerable cost savings can be generated by utilizing automated process control schemes even if they are less than optimum.

B. SLUDGE CONDITIONING

In September of 1974 EPA sponsored a workshop to identify the research required to promote the cost-effective automation of wastewater treatment facilities. The working party addressing sludge processing needs recognized that sludge conditioning processes were not fully understood and thus recommended that the initial stage of research involve empirical evaluation. (1) Ongoing research sponsored by MWCC (2)(3)(4) and more than 30 years experience dewatering chemically conditioned sludge at MWCC's Metro Plant demonstrated the importance of efficient chemical conditioning prior to dewatering on vacuum filters.

The dewatering characteristics of a conditioned sludge can be adequately described by its specific resistance, R_S, as defined by Gale (5). The value of the specific resistance is easily determined by using the standard Buchner Funnel apparatus (6); however, it cannot presently be determined by automated means. The specific objective of one of the major aspects of the project was to develop and implement a model of the specific resistance based on sludge parameters that could be quantified using field instruments. It was reasoned that a control scheme could be readily designed to manipulate the chemical feed rates and thus maintain a relatively constant value of specific resistance while minimizing chemical use.

C. VACUUM FILTER CONTROL

The justification for automated control of a dewatering device may be economic but is also related to the specific operating goal. Because the solids handling facilities at Seneca are operating near capacity, the operating goal has been to maximize the volume of liquid sludge pumped to the vacuum filters. Figure 3 demonstrates that, under manual control, the characteristics of the filter cake vary substantially. If the cake was discharged to storage for subsequent disposal on land or volume reduction by incineration further control schemes might not be justified. In the case of Seneca, however, the cake discharges directly to the incinerators and the variation in cake moisture and volatile content result in unstable incinerator operation which is manifested by smoke discharges and large temperature excursions.

The overall objective of the control scheme was to maintain steady state operation and at the same time maximize the filter yield in terms of dry sludge solids. It has been demonstrated that, what is herein termed the yield equation, Eq. [1], is an adequate steady state model for vacuum filtration when the filter media resistance is negligible. (7) It was reasoned that this relationship could be used to setpoint the individual controls for drum speed, submergence and vacuum and thus maintain a relatively constant yield.

The yield equation is as follows (8):

$$[1] \quad L = \left[\frac{2\,Pwk}{\mu Rs\ Tc}\right]^{\frac{1}{2}}$$

WHERE: L = dry solids yield - kg/m^2 sec
P = form vacuum - N/m^2
w = weight of cake per unit volume filtrate - kg/m^2
μ = filtrate viscosity - $N\ sec/m^2$
R_s = specific resistance - $\frac{sec^2\ lbf}{lbm^2}$
T_c = cycle time - sec
k = fraction of cycle time in form zone--no unit

Note that many texts do not use a consistent set of units when presenting the yield equation; and, the coefficient may thus vary substantially for various references. In this report the yield will be expressed as above; however, the specific resistance will be reported in terms of the SI system - m/kg.

D. INCINERATOR CONTROL

The basic automated control scheme for incinerators consists of separate control of each set of burners, based on temperature setpoint, along with control of the incinerator's negative pressure. Although each of the controls by itself may be a textbook example of basic control technology, in actual practice they do not function well because of the considerable interaction. Great care in choosing setpoints is required; because, it is easy to choose values that are mutually exclusive.

The initial objective was to develop and integrate a total of six control loops as follows:

Loop	Controlled Device	Feedback
1	Rabble Arm Drive	Temperature
2	Coal Feed	Energy Use
3	Hearth 3, 5, 6 Burners	Temperature Profile
4	Hearth 1 Burner	Temperature
5	Induced Draft Damper	Furnace Pressure/Oxygen
6	Combustion Air	Temperature/Oxygen

Preliminary algorithms were prepared for each control scheme; however, testing and implementation was not always accomplished. The proposed rabble arm control scheme was of the feed forward type using feed rates of dry solids and water to adjust rabble arm speed and thus residence time in the incinerator. All attempts at online cake moisture measurement failed; and, the control scheme was thus dropped from further development.

Previous work at the Seneca facility indicated that coal and/or processed refuse may be used as an alternative fuel for incineration. (9) Since the completion of that project, however, no action was taken to implement the use of alternative fuels and development of the control algorithms terminated.

The purpose of loop 4 was to demonstrate the feasibility of maintaining an incinerator exit temperature of 650°C (1200°F) to control odors. The proposed algorithm required cake moisture information. Because of this and the cost required to put the burners into service, no further action was taken.

It was possible to implement the remaining control loops primarily because of concurrent work conducted by MWCC's Operation Department--Quality Assurance Division. The purpose of that project was to determine incinerator operating procedures that would yield compliance with stack discharge standards. It was relatively simple to control the temperature profile, draft, and air after the setpoint ranges were determined.

SECTION 7

FIELD INSTRUMENTATION

A. GENERAL

A variety of instruments were installed during the project period to provide process data. These data were used for the development of models and control algorithms and eventually for actual process control. Existing plant instrumentation was utilized whenever possible. The output signals from all field instruments were modified as necessary to provide a uniform 4-20 ma format. All outputs were eventually wired to one of the two remote terminals located in the control room of the solids processing building.

Field instruments were initially installed only in train no. 1 because vacuum filter no. 1 and incinerator no. 1 were to be automated. Because of the continuous evaluation of instruments and control strategies not all of the instruments originally procurred were utilized in the final version of the various control loops. Later in the project some instrumentation was installed in process train no. 2 to provide the data necessary to compare manual and automated control schemes.

B. SLUDGE CONDITIONING

1. Flow

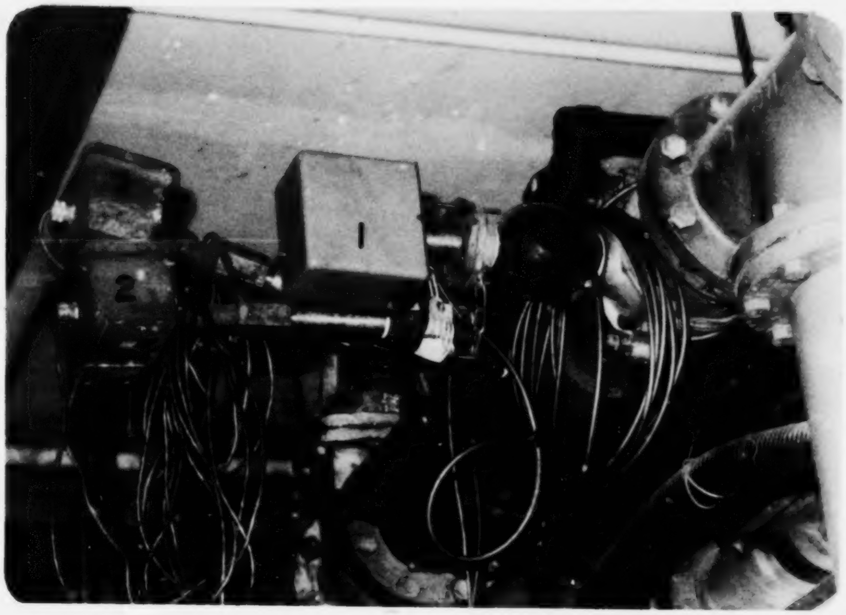
Raw sludge flow to each vacuum filter is measured with a Fischer-Porter magnetic flow meter (Model 10D1416C) installed in the 15 cm (6 inch) sludge pipe approximately 6 m (20 ft) downstream from the raw sludge pumps. The flow rate is displayed by the flow totalizers located in the operating control room.

2. Solids Concentration

Optical type Biospherics Model 52 H solids analyzers were installed in the influent sludge pipes serving filters 1 and 2. The analyzers were located approximately 3 m (10 ft) downstream of the sludge pumps and were mounted in a valve assembly which allowed the monitor to be removed from the pipe without complete dewatering. The control units were mounted adjacent to the analyzers and provided a meter reading in the range of 0 to 10 percent solids. The mounted analyzer and control assembly are illustrated in Figure No. 4.

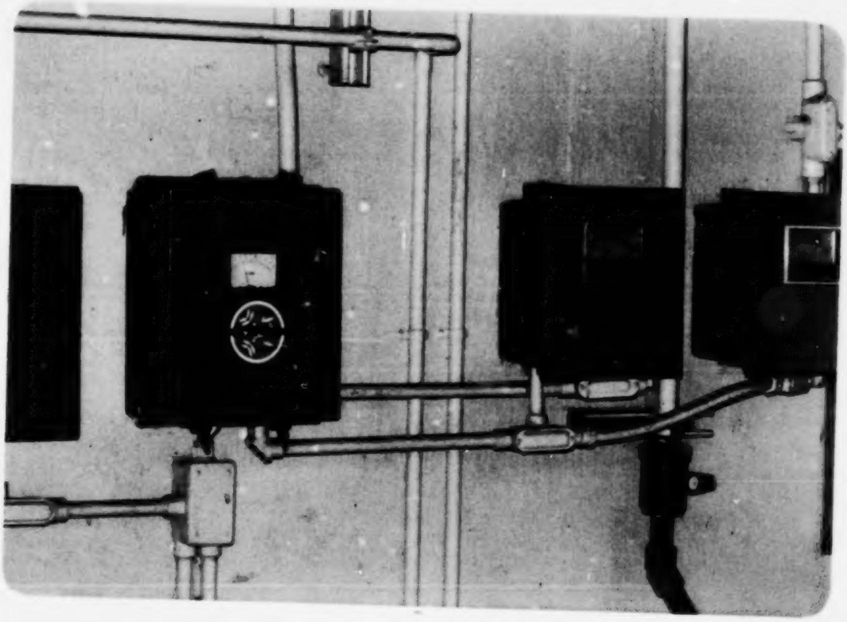
3. pH

The raw and ferric conditioned sludge pH were originally monitored with



(A) SENSORS

(1) SOLIDS
(2) ORP
(3) pH



(B) READOUT

Figure 4. Raw sludge analyzers.

Leeds and Northrup pH receiver units, transmitters, and 3-electrode flow-through mountings including automatic temperature compensation. Positive displacement pumps were used to provide samples of the raw and ferric chloride conditioned sludge. The 2.5 cm (1 in) suction lines of the pumps frequently plugged at the point where they joined the 15 cm (6 in) sludge pipe. In addition the seal water used to protect the pump bearings periodically leaked into the pump discharge and impacted pH measurements. Because of these difficulties the pump and flow-through installations were replaced with pipe insertion mountings using a single combination-type pH electrode. The signal transmitter was located directly adjacent to the electrode as part of the installation (L & N model 7774 mounting). The revised installation utilized manual temperature compensation.

The raw sludge pH monitoring instrumentation was mounted adjacent to the raw sludge solids analyzer approximately 4 m (12 ft) downstream of the sludge pumps. The pH receiver unit was mounted on the basement wall near the pH electrode installation. The installation is illustrated in Figure No. 4.

The ferric chloride sludge pH electrode was mounted in the sludge pipe approximately 1 m (3 ft) below the sludge conditioning tank on the vacuum filter floor as illustrated in Figure No. 5. The pH of the lime conditioned sludge was monitored in the outfall stream of the conditioning tank again using a combination pH electrode. The ferric chloride and lime sludge pH receivers were mounted in the operating control room.

4. ORP

The redox potential of raw and ferric chloride conditioned sludges was monitored with Leeds and Northrup combination platinum redox electrodes, transmitters and receiver units. The electrodes were located next to the respective raw and ferric chloride conditioned sludge pH installations--see Figures 4 and 5. Pipe insertion mountings identical to the pH mountings were used for the electrode and transmitter in both installations.

5. Viscosity

The viscosity of the lime conditioned sludge was monitored with a Brookfield process viscometer, Model VTPV (0-500 centipoise), mounted in the sludge conditioning tank. A 122 cm (48 in) baffle tube, housing a motorized spindle, was suspended approximately 10 cm (4 in) beneath the sludge surface. A screen was attached to the bottom of the tube to protect the spindle from rags and other foreign material present in the sludge. The output signal from the viscometer was wired to a chart recorder during instrument evaluation.

C. FILTRATION

1. Vat Level

The vat level of each vacuum filter was monitored using a sonic type level sensing device manufactured by Endress and Hauser, Inc. (type ECHO 1 SDL with a TWLA sensor). The temperature compensated receiver-transmitter was

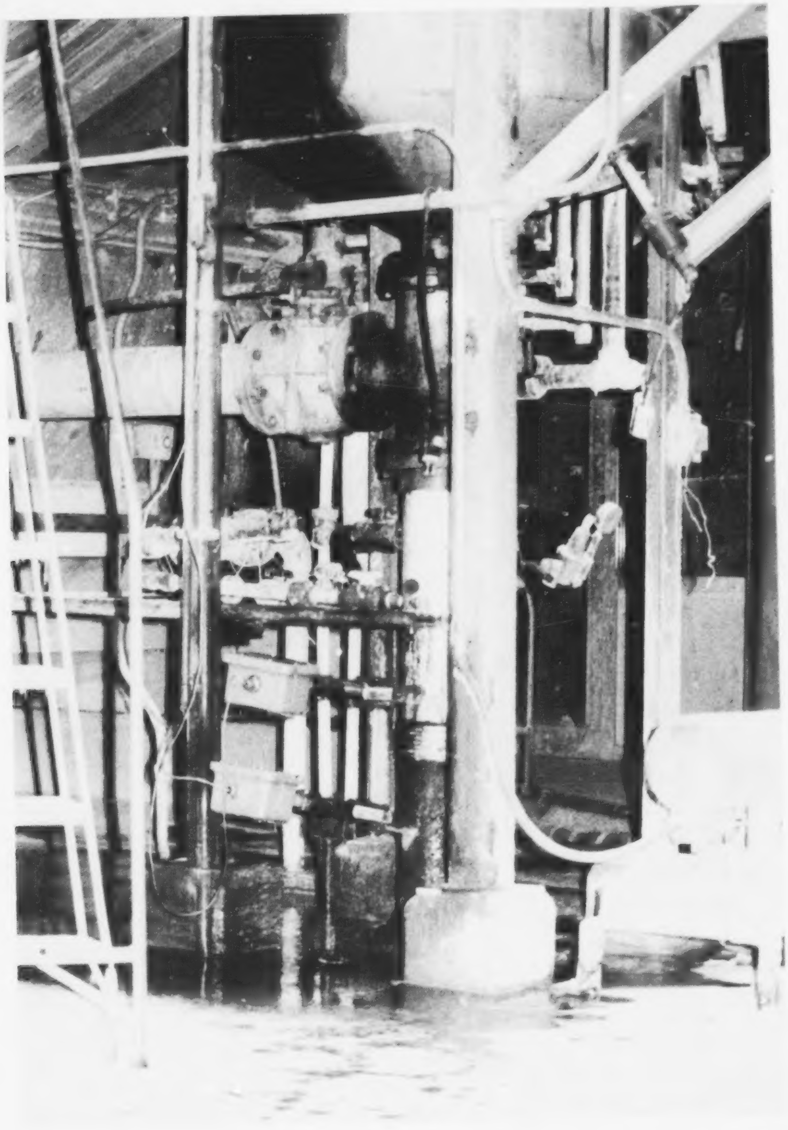


Figure 5. Inlet to sludge conditioning tank.

mounted over a 7.6 cm (3 in) diameter baffle tube, 147 cm (58 in) in length suspended into the filter vat as illustrated in Figure 6. The instrument was calibrated over a measurement range of 91 cm (36 in).

2. Rotational Speed

Rotational speed measurement and control devices were installed on the automated filter drum drive, agitator and sludge conditioning tank mixer. Remote controlled pilot motors were mounted to replace the local manual speed control devices at the three locations. Tachometer generators were installed on each drive unit for rotational speed transmission. Identical tachometer generators were also installed on the manually controlled filter.

3. Vacuum

Rosemount vacuum transmitters with a range of 0-76 cm (0-30 in) Hg were mounted on the manual and automated vacuum filters to monitor the form and dry vacuum generated at each filter. A 7.6 cm (3 in) butterfly valve with an electric operator was installed in the form vacuum line of filter no. 1 to provide remote control of the form vacuum. A potentiometric output (converted to 4-20 ma at the remote terminal) provided an indication of the valve's position.

4. Turbidity

A Hach surface scatter turbidimeter was mounted in the basement of the solids processing building to monitor filtrate turbidity. The wall-mounted unit received a continuous filtrate sample of approximately 2 l/min (0.5 gpm) which was pumped from the filter vacuum receiver through approximately 38 m of (125 ft) of 2.54 cm (1 in) PVC pipe. Two debubbling chambers, mounted in series, were located immediately adjacent to the turbidimeter to provide a bubble-free sample.

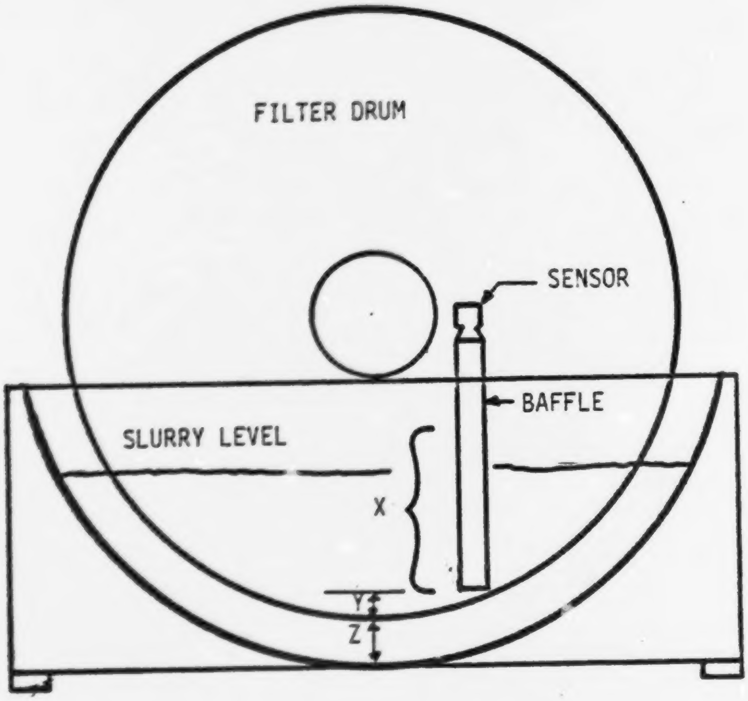
5. Cake Thickness

Cake thickness was measured by an ultrasonic level monitoring device manufactured by Wesmar (Model SLM-2). The sensor was mounted approximately 25 cm (12 in) above the filter drum at the beginning of the cake drying zone. The instrument was calibrated over a 0-25 mm (0-1 in) measurement span. A temperature compensation option was added to reduce output error caused by temperature changes. An adjustable mounting bracket was constructed so that the sensor position could be readjusted for calibration against fixed targets.

6. Cake Yield

a. Weight

Filter cake weight was measured by existing weigh scales manufactured by Thayer, Inc. (Model I-128). The weight measurement is based on the combined outputs of a load cell mounted beneath the inclined cake conveyor and a belt speed transmitter located at the conveyor driver roller. The instantaneous 4-20 ma output signal representing weight per unit time was conditioned using



NOTE: X = SPAN = 91 cm (36 in)
Y = 13 cm (5 in)
Z = 20 cm (8 in)

Figure 6. Schematic of vat level measurement system.

a signal averaging module in order to dampen scale output fluctuations caused by uneven cake loading. An identical conditioning module was installed on the scale output serving filter no. 2.

b. Moisture

A number of moisture analyzers were evaluated under on-line operating conditions to determine if an instrument could provide a continuous measure of cake moisture. An initial evaluation of an infrared instrument (manufactured by Anacon, Inc.) mounted over the vacuum filter was not successful. Further testing was conducted to evaluate instruments manufactured by Moisture Systems Corp. (infrared), Moisture Register Co. (infrared), Strandberg Engineering Laboratories, Inc. (microwave), Ohmart Corp. (infrared) and Anacon, Inc. (infrared).

The infrared method of analysis is based on the difference in reflected energy between two wavelengths of infrared light directed at the filter cake, one of the wave lengths being absorbed by water molecules present in the sample. The microwave analysis method is based on the amount of microwave energy reflected compared to the total energy applied. All of the instruments based their measurements on the water present in the upper layers of sample and were therefore not capable of detecting all of the water in a given sample.

D. INCINERATION

1. Temperature

Incinerator hearth temperatures are measured with chromel-alumel type K thermocouples mounted through the hearth wall. Each thermocouple is protected by a metallic housing. The voltage signals generated by the thermocouples mounted in incinerator no. 1 were converted to 4-20 ma outputs to facilitate computer monitoring. Two stripchart recorders provide local printout of the hearth temperatures at two-minute intervals for each incinerator.

2. Fuel Flow

Natural gas flow to each incinerator is monitored by an American Meter Co. 10 cm (4 in) gas turbine meter installed in the inflow piping. The meter output was compensated for temperature and pressure. Both instruments provided a local totalizer. The flow meter serving incinerator no. 1 was installed with a pulse transmitter to provide a continuous output signal.

Two Niagara 2.54 cm (1 in) flow meters (supply and return) were installed on each incinerator to monitor fuel oil flow. Each flow meter was installed with a pulse transmitter. Low frequency conversion modules located in the incinerator remote terminal converted the pulse signal to a 4-20 ma output two transmitters to provide a single output representing net fuel oil consumption.

3. Oxygen Concentration

The flue gas from the incinerator no. 1 was monitored with a Dynatron Model 2100 insitu oxygen analyzer. The analyzer was located in the incinerator breech adjacent to hearth no. 1 as show in Figure 7. The oxygen probe was installed with a defletor plate to prevent the gas diffusion element from becoming clogged with ash. The diffusion element protects the sensor from contamination but allows oxygen to diffuse to a zircronium oxide cell which is heated to 815°C (1500°F). The oxygen concentration measurement is based on the difference in potential developed across the zircronium oxide cell. One side of the cell is exposed to the sample gas while the other is exposed to reference gas containing a known oxygen concentration.

A calibration gas control panel was constructed to allow calibration with various reference gases. The cell output signal was transmitted to the control unit located in the operating control room and to the incinerator remote terminal. The control unit displayed the current oxygen reading as well as the cell temperature and resistance.

4. Shaft Speed

The rabble arm shaft speed was monitored using a metal sensitive proximity switch mounted at the base of the incinerator shaft. The switch produced a pulsed signal when passing over equally spaced metal screws attached to the shaft. The pulsed signal was converted to 4-20 ma by a low frequency transmitter and relayed to a local RPM meter (0-3 RPM) as well as the incinerator remote terminal.

5. Pressure Differential

Incinerator draft pressure is measured on hearth No. 1 by a Foxboro Model E13DL differential pressure cell. A 10-50 ma signal is transmitted to an indicating controller and draft indicator located in the incinerator control panel and to the incinerator remote terminal.

6. Valve and Damper Position

Potentiometric inputs from burner combustion air valve, induced draft, atmospheric air, shaft return air, and scrubber inlet damper positioners are relayed to position indicators in the incinerator control room. The potentiometric signals were converted to 4-20 ma outputs by signal converters and relayed to the incinerator remote terminal.

E. MISCELLANEOUS

1. Holding Tank

The sludge level in each holding tank was monitored by an ultrasonic level sensor manufactured by Inventron Industries, Inc. The sensor, which was mounted above the holding tank, acts as a transmitter of ultrasonic waves and as a microphone pickup of return echoes. The output of the sensor (with temperature compensation) was fed to a control unit mounted approximately 3 m (10 ft) from the sensing head. The control unit contained calibration adjustments

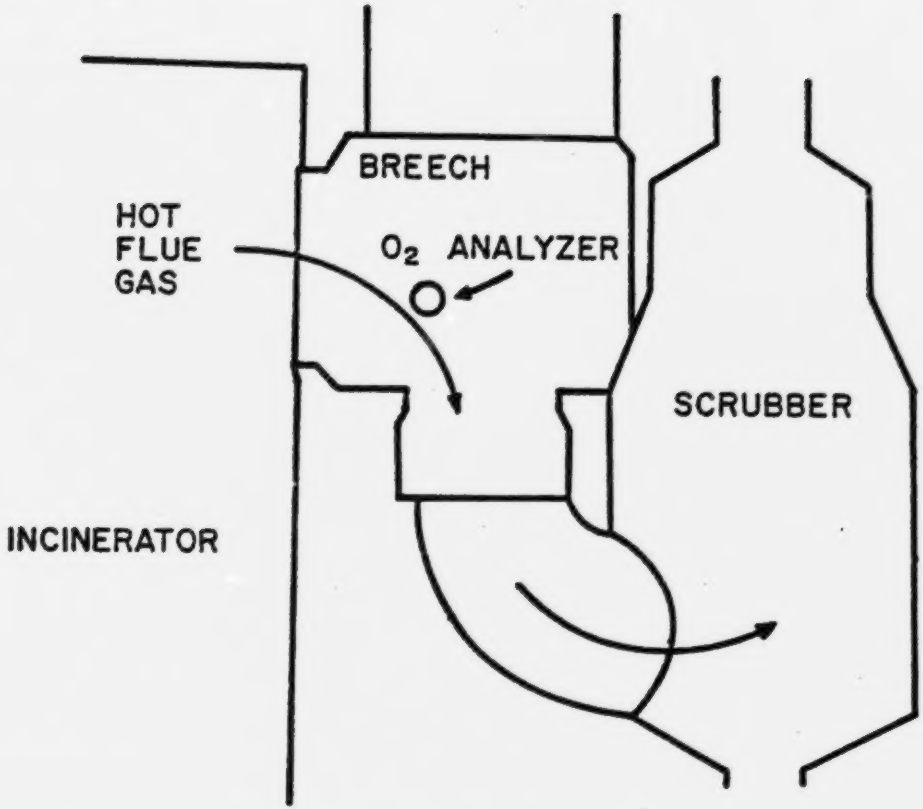


Figure 7. Location of flue gas oxygen analyzer.

and provided a 4-20 ma output which was relayed to a local meter in the operating control room and to the vacuum filter remote terminal.

2. Chemical Feed

a. Ferric Chloride

Pulse frequency transmitters were installed to monitor the discharge rate of the two ferric chloride diaphragm pumps. The frequency of discharge of each pump was controlled by an electrically activated valve which supplied the air to the diaphragm. The activation signal for the solenoid valve was relayed to a pulse transmitter which converted the pulse rate to a 4-20 ma output. The output signal was converted to a flow rate by applying the measured discharge volume per cycle. Ferric chloride concentrations were determined manually and entered through the CRT. Computer control signals to the automated ferric chloride pump were transmitted through a current to pulse transducer having an output range of 3-40 pulses/min.

b. Lime

The lime flow rate was calculated based on the measured pump speed and the discharge calibration curve. Computer control signals to the lime pump serving filter no. 1 were transmitted through a voltage to current module.

A density analyzer manufactured by Dynatrol was installed to monitor the lime slurry concentration. Analyzer output was based on changes in resonant frequency caused by variations in sample density as it passed through a 1.27 cm (0.5 in) diameter flow tube. Although the instrument output was correlated to lime density in several tests a sufficient flow of lime could not be provided on a continuous basis. Because of the sampling problems the analyzer was not utilized. Lime concentrations were therefore measured manually and entered through the computer CRT.

SECTION 8

COMPUTER FACILITIES

A. GENERAL

In order to address the overall objective of modeling and controlling the solids processing train the data collection and control schemes required a considerable degree of flexibility. In the planning stages a large number of control loops were considered, some simple and some complex; and, it became rather obvious that there would be interaction between many of the loops. It was anticipated that the control schemes might change significantly from the conceptual stage to the operational stage. In addition the magnitude of the data collection task essentially required the selection of a computer based system.

The computer facilities were designed and built in two phases. In the initial phase, only the vacuum filter was considered; and, the basic system was designed for this level of capability. Approximately two years later the incinerator was added to the project scope. Modifications were then made to substantially increase the capability of the system.

The purpose of this section is to describe the capabilities of the computer facilities. Detailed design considerations are presented in Appendix A. The description of the intermediate facilities is also left to that appendix. The capabilities of the final system only are discussed here.

B. SYSTEM DESCRIPTION

The computer system is built around a Data General Nova 3/12 central processing unit (CPU) with 32,768 words of core memory. The Nova 3 class computer was a small mini-computer in 1977 terms. A Data General 5 million word moving head disk (MHD) that provides mass memory for program storage and data storage is an integral part of the computer. A large amount of standard software was provided with the hardware. In particular, the RDOS (real-time disk operating system) version 6.33 operating system provided software that permitted immediate access to programs on the disk. The development of application programs relevant to the project was thus possible.

Program development capability was provided via a keyboard printer (DEC LA120). The operator's station was designed around a standard 80 character by 24 line black and white CRT (ADDS 580). A second printer with keyboard was available and used mainly as a time share terminal to the

University of Minnesota computer complex. Two remote terminal units (RTUs) were installed near the process equipment and provided input and output capabilities. The computer configuration is illustrated in Figure 8.

The application programming was divided into two categories, system programming and control programming. The system programming included the development of a simple process control language (a compiler), an operator's console driver (a monitor), a report generator, and resource routines for accessing disk resident files and communication ports to the RTUs.

The control programming was all done using the process control language and included the development of a data acquisition system to bring data into the computer from the RTUs, control modules, such as PID controllers for use in control loop strategies, an alarm and event logging system, and trending package. The report generator was used to develop operator displays and reports.

C. DATA COLLECTION CAPABILITY

1. On-Line Sensor Data

The data collection capability is organized into three parts, the scanning or reading of connected sensors, the dedicated data reporting, and the optional trending of data.

Each RTU provides the capability to connect up to 36 analog inputs, e.g., sensors. The sensors are mounted in the process flow or on a device controlling that flow and provide a continuous output or reading of the measurement. Examples of on-line sensors include flow meters, weigh scales, thermocouples, and tachometers. If the appropriate sensors are available most of the data collection can be automated using the computer facility. If sensors are not available the determinations must be made manually via sampling and laboratory analysis.

Each sensor connected to the RTU is scanned by the computer once every 10-15 seconds and its value stored in memory. The capability to individually calibrate each value, scale it to engineering units, and smooth it with a first order filter is provided as part of the data acquisition software. High and low alarm limits may also be assigned for each analog value.

The data acquisition software provides two values for each analog input (sensor), the current value after smoothing, scaling, etc., and the average for the last hour based on every scan during that hour. Intermediate averages may be added in the control software.

2. Dedicated Reporting

Several preprogrammed reports are used to provide hard copy of significant data summaries. These reports provide the operators with concise information which allow them to make judgements related to potential process changes.

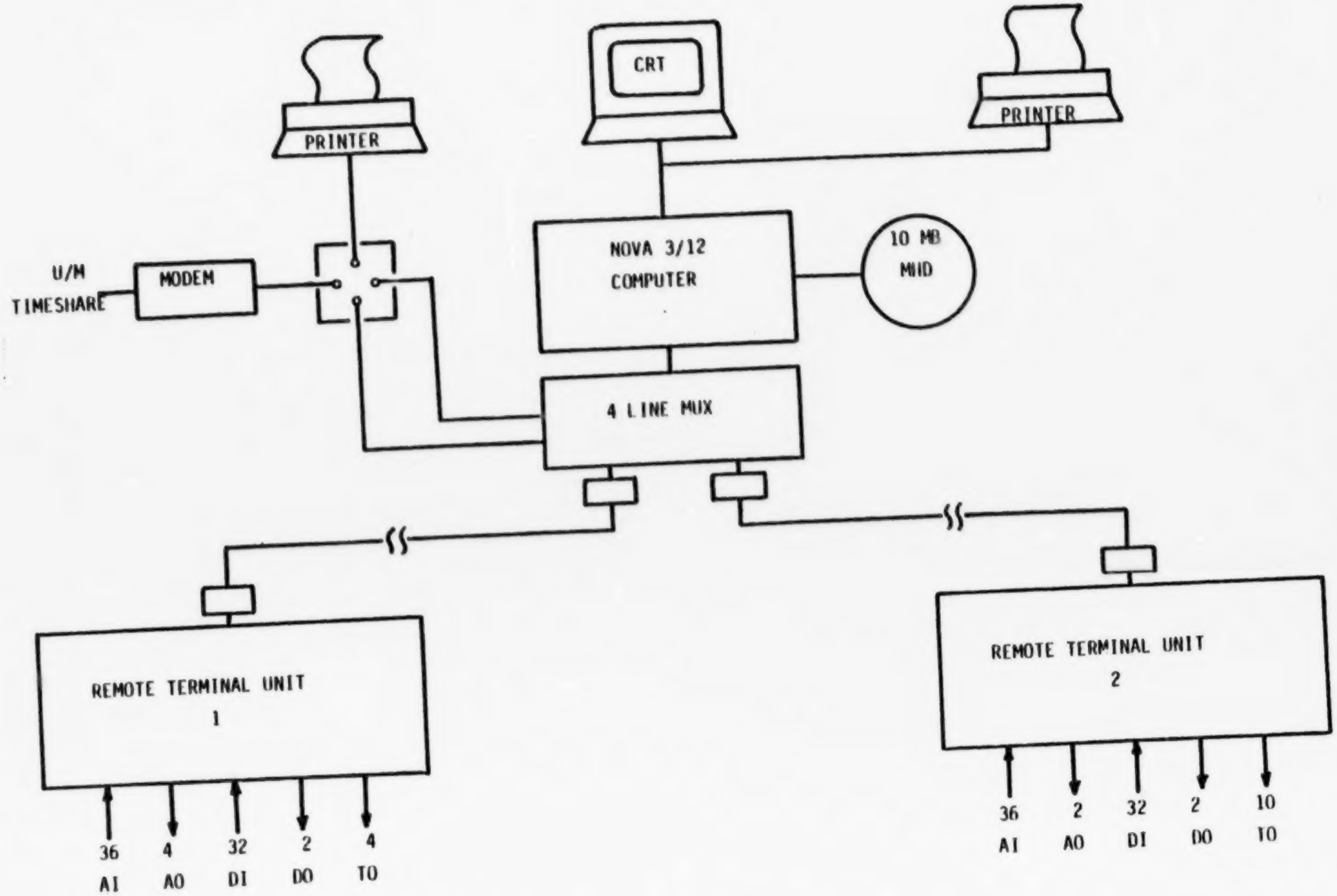


Figure 8. Computer configuration.

The Hourly Report is produced at the end of each hour. It provides an hourly average value for each analog input in engineering units. The operational status of the various devices is also summarized. The hourly report for June 9, 1981, hour 23 (10:00 p.m. to 11:00 p.m.) is presented in Figure 9. The point descriptions are summarized in Appendix A.

The Shift Report is printed at the end of each shift (7:00 A.M., 3:00 P.M., and 11:00 P.M.). This report is organized by process; and, a separate report is printed for each filter. No report, however, was programmed for the incinerators during the project. The Shift Report presents a series of eight hourly averages and an eight-hour average for selected parameters of interest to the plant operator. The report for the period 3:00 P.M. to 11:00 P.M. of June 9, 1981 for filter no. 1 is presented in Figure 10. In this report the time at the beginning of the hour is used to identify the hourly average, e.g., hour 2200 represents the period 10:00 P.M. to 11:00 P.M. For 1600 hr all values are reported as zero. This does not mean that filter no. 1 was out of service for the period 4 P.M. to 5 P.M.; but, it implies that the computer was out of service shortly after 5 P.M. If an hourly report is not printed on schedule the data for that hour are lost.

The 24-Hour Report is printed at 11:00 P.M. each day and summarizes for the plant superintendent several significant parameters. The report for June 9, 1981 is presented in Figure 11. This report allows the superintendent to rapidly compare the performance of the shifts and filters.

A continuous alarm log is printed to indicate when an input exceeds an alarm limit. Included in the alarm message is the value of the input and the value of the limit exceeded along with point identification and time/date stamp.

3. Trending and Displays

The trending program provides hard copy printout of selected values, such as analog inputs, on a timed interval basis. The interval can be selected in the range of 0.5 min to 60 min. Up to 32 values can be trended simultaneously. The setup of the trend, which includes assigning points to the trend and setting the time interval, is done through the CRT console. Since only about 8-9 values will fit across the paper on a line, the trend is designed to print up to 4 lines of data with each line containing 8 values. The first line begins with the time stamp. The following lines are labeled line 2, 3, and 4. An example of the trend log is provided in Figure 12. This program provides trends of analog inputs, calculations, outputs, and any other interval value in memory.

The operator displays provide access to all data in the system on the most frequent interval. The screen is refreshed about every 5-10 seconds. Data collected by the system can be logged manually from the displays if so desired.

The report generator provides the capability to easily build special reports whenever desired. The 24-hour report is an example of a special report that was maintained as a dedicated report.

```
                 SENECA WWTP HOURLY AVERAGES REPORT

        HOUR 23                                         06:09:81  23:01:04

********************************* HOURLY AVERAGES *********************************

   0  FL1R          72.98  GPM          36                      .00
   1  PHR            5.54  PH           37  AMBZ            -138.92  PCT
   2  ORPR        -328.93  MV           38  O2                 6.67  PCT
   3  PHF            5.32  PH           39  EA               118.15  PCT
   4  L1FL           9.69  GPM          40  RCAZ              27.76  PCT
   5  PHL           11.92  PH           41                      .00
   6  ORPF         -60.66  MV           42  IDF7              73.61  PCT
   7  SS1R           4.71  PCT          43                      .00
   8  FL2R          41.27  GPM          44                      .00
   9  VAT1          15.52  IN           45  H3Z1              79.39  PCT
  10  VAT2          16.27  IN           46  H3Z2              75.27  PCT
  11  L2FL           9.91  GPM          47  H5Z1              93.87  PCT
  12  WT1            6.41  TPH          48  H5Z2              98.83  PCT
  13  MOIST         16.85  PCT          49  H6Z1                .00  PCT
  14  WT2            5.26  TPH          50  H6Z2                .00  PCT
  15  SS2R           4.50  PCT          51                      .00
  16                  .00               52  RAST               1.85  RPM
  17  THIK            .33  IN           53  H1T              717.15  DEF
  18  F1FL           2.49  GPM          54  H2T              996.40  DEF
  19  F2FL           2.93  GPM          55  H3T             1349.87  DEF
  20  FRMZ          89.94  DEGR         56  H4T             1369.00  DEF
  21  FRM1           8.31  INHG         57  H5T             1465.18  DEF
  22  FRM2           5.12  INHG         58  H6T              901.56  DEF
  23                  .00               59  H7T              260.70  DEF
  24  SLK1         191.87  #PM          60  DFTP               -.18  PSI
  25  SLK2         174.07  #PM          61  SRDP               5.12  INH2O
  26  D1ST          14.26  RPH          62  OIL1                .00  GPM
  27  D2ST          11.32  RPH          63  FUE1                .00  GPM
  28  A1ST          10.62  RPM          64  GAS1             105.85  SCFM
  29  A2ST          10.02  RPM          65  OIL2                .00  GPM
  30  DRY1           9.82  INHG         66  FEU2                .00  GPM
  31  DRY2           6.32  INHG         67  GAS2                .59  SCFM
  32  MIX1          33.99  RPM          68  RCAT             222.11  DEF
  33  MIX2          46.82  RPM          69  SR1T             181.64  DEF
  34  HT1L            .00  FT           70  IDFT              92.38  DEF
  35  HT2L            .00  FT           71                      .00
********************************* % DEVICE IN AUTO *********************************

   SLDG P1      .0    DRUM D1   100.0    BURN H3   100.0    IDFN DF   100.0
   SLDG P2   100.0    AGIT D1      .0    BURN H5   100.0    SCRB DF      .0
   FECL P1   100.0    MIXR D1      .0    BURN H6      .0    COOL DR   100.0
   LIME P1   100.0    FVAC V1      .0    RARM DR      .0    ATMA DR      .0

******* VF#1***************  VF#2**************  INC#1*************  INC#2******

  SLDG GAL  4379.00   SLDG GAL  2476.75   UNDEFIND        0   UNDEFIND        0
  SLDG LBS  1722.78   SLDG LBS   930.75   UNDEFIND        0   UNDEFIND        0
  FECL LBS   199.67   FECL LBS   235.04   UNDEFIND        0   UNDEFIND        0
  LIME LBS   345.85   LIME LBS   353.96   UNDEFIND        0   UNDEFIND        0
  CAKE TON     6.41   CAKE TON     5.26   UNDEFIND        0   UNDEFIND        0
  CAKE SOL    15.91   CAKE SOL    12.99   UNDEFIND        0   UNDEFIND        0
  %OPERAT    100.00   %OPERAT    100.00   UNDEFIND        0   UNDEFIND        0
```

Figure 9. Hourly report for 2300 hr on June 9, 1981.

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```
SENECA WASTEWATER TREATMENT PLANT
                                                         DATE 06:09:81
                 SHIFT REPORT VACUUM FILTER 1            TIME 23:05:08
---------------------------------------------------------------------------------
PROCESS DATA  *  1500    1600    1700    1800    1900    2000    2100    2200  TOTALS
---------------------------------------------------------------------------------

INPUT SLUDGE
 FLOW     GPM *  58.2     .0    59.6    58.0    71.6    69.2    70.3    72.9    57.5
 TOT FLOW GAL *3494.1     .0  3579.5  3480.3  4298.7  4156.2  4221.2  4379.0 27608.0
 SS       %   *  4.52    .00    4.41    4.54    4.70    4.76    4.81    4.71    4.06
 SOLIDS   LBS *1317.1     .0  1317.7  1318.8  1687.7  1649.8  1696.0  1722.7 10710.0
 PH           *  5.45    .00    5.56    5.57    5.54    5.50    5.50    5.54    ---
  MODE P1 %C  *    .0     .0      .0      .0      .0      .0      .0      .0      .0
  MODE P2 %C  *    .0     .0      .0    94.4   100.0   100.0   100.0   100.0    61.8

FERRIC CHLORIDE
 FLOW     GPM *   1.8     .0     2.0     2.1     2.4     2.3     2.0     2.4     1.9
 TOT USED LBS * 151.2     .0   165.7   173.8   196.8   189.0   162.6   199.6  1239.0
 CONC    LBPG *  1.33    .00    1.33    1.33    1.33    1.33    1.33    1.33    1.16
 PH           *  5.56    .00    5.33    5.27    5.39    5.26    5.26    5.32    ---
  MODE    %C  *    .0     .0      .0    81.1    73.8   100.0   100.0   100.0    56.8

LIME
 FLOW     GPM *   7.4     .0     6.9     9.0     9.3     9.2     9.5     9.6     7.6
 TOT USED LBS * 265.9     .0   248.3   321.5   332.0   330.8   339.8   345.8  2184.2
 CONC    LBPG *   .59    .00     .59     .59     .59     .59     .59     .59     .52
 PH           * 12.02    .00   11.83   11.90   11.94   11.93   11.85   11.92    ---
 LIME DOSE  % *  20.1     .0    18.8    24.3    19.6    20.0    20.0    20.0    17.9
  MODE     %C *    .0     .0      .0    83.0   100.0   100.0   100.0   100.0    60.3

VACUUM FILTER
 OPERATION %  * 100.0     .0    96.5    75.3   100.0    95.5   100.0   100.0    83.4
 DRUM DRV RPH * 12.20    .00   12.10   12.35   13.85   12.86   14.61   14.26   11.53
  MODE    %C  *    .0     .0      .0    64.7   100.0    88.5   100.0   100.0    56.6
 AGITATOR CPM *  10.6     .0    10.3    10.5    10.6    10.6    10.6    10.6     9.2
  MODE    %C  *    .0     .0      .0      .0      .0      .0      .0      .0      .0
 FORM VAC  IN * 11.63    .00   10.81    9.57    9.18    9.08    9.05    8.31    8.45
 DRY VAC   IN * 13.95    .00   12.89    7.44   11.53   10.89   11.33    9.82    9.73
 VAT LVL   IN * 19.46    .00   18.72   18.48   13.58   15.45   15.59   15.52   14.60

FILTER CAKE
 ON DRUM   IN *   .33    .00     .11     .28     .33     .34     .32     .33   59368
 CONVEYED TPH *   5.3     .0     4.5     4.7     5.8     5.7     5.8     6.4     4.8

 SLDS CALC %  * 14.54    .00   17.01   17.15   17.07   17.01   17.04   15.91   14.46
---------------------------------------------------------------------------------

LAB DATA
 MOISTURE  %  * -----  -----   -----   -----   -----   -----   -----   -----   -----
 VOLATILES %  * -----  -----   -----   -----   -----   -----   -----   -----   -----
```

Figure 10. Shift report for relief shift on June 9, 1981.

```
                SENECA WASTEWATER TREATMENT PLANT

                                                    DATE 06:09:81 /
                          24 HOUR REPORT            TIME 23:07:57

----------------------------------------------------------------------------------
H *           VACUUM FILTER #1               *         VACUUM FILTER #2          *
O *------------------------------------------------------------------------------*
U *    %   FEED  %    %    %   CAKE  %    %  *  FEED  %    %    %   CAKE  %    % *
R *  AUTO  GPM  SOL IRON LIME  TPH SOL  VOL  *  GPM  SOL IRON LIMF  TPH SOL  VOL *
----------------------------------------------------------------------------------
  *                                          *                                   *
23 *    .0  60.5 4.7 12.6 20.7 4.0   .    .  *  30.3 4.5 20.3 63.6 3.7   .    .  *
00 *    .0  62.5 4.6 12.0 20.2 5.1   .    .  *  42.7 4.5 15.2 53.9 4.0   .    .  *
01 *    .0  61.9 4.6 11.8 20.2 5.0   .    .  *  29.5 4.6 21.7 61.0 2.0   .    .  *
02 *    .0  61.7 4.5 10.6 21.1 5.0   .    .  *    .0 4.7   .0   .0  .8   .    .  *
03 *    .0  61.6 4.7 10.3 20.1 5.0   .    .  *    .0 4.8   .0   .0  .8   .    .  *
04 *    .0  61.9 4.7 10.3 19.9 5.0   .    .  *    .0 4.8   .0   .0  .8   .    .  *
05 *    .0  62.7 4.7 10.1 19.8 5.0   .    .  *    .0 5.0   .0   .0  .8   .    .  *
06 *    .0  61.6 4.6  9.8 20.4 5.1   .    .  *    .0 5.1   .0   .0 2.3   .    .  *
   *                                         *                                   *
 AVE    .0  61.8 4.6 10.9 20.3 4.9   .    .  *  12.8 4.8  7.1 22.3 1.9   ..   .  *
   *                                         *                                   *
   *                                         *                                   *
07 *    .0  61.1 4.5 10.2 22.2 4.8   .    .  *    .0 5.1   .0   .0 3.4   .    .  *
08 *    .0  62.0 4.6 10.2 18.5 5.3   .    .  *    .0 5.0   .0   .0 3.2   .    .  *
09 *    .0  60.4 4.5 11.5 20.4 5.4   .    .  *    .0 4.9   .0   .0 3.3   .    .  *
10 *    .0  57.5 4.5 11.8 22.0 5.7   .    .  *    .0 5.1   .0   .0 3.2   .    .  *
11 *    .0  59.1 4.5 11.3 19.8 5.6   .    .  *    .0 4.9   .0   .0 3.3   .    .  *
12 *    .0  61.1 4.4 11.1 19.2 5.5   .    .  *    .0 4.8   .0   .0 3.3   .    .  *
13 *    .0  59.7 4.4 11.5 19.6 5.3   .    .  *    .0 4.5   .0   .0 3.3   .    .  *
14 *    .0  58.4 4.6 11.3 22.7 5.4   .    .  *    .0 4.7   .0   .0 3.2   .    .  *
   *                                         *                                   *
 AVE    .0  59.9 4.5 11.1 20.5 5.4   .    .  *    .0 4.9   .0   .0 3.3   .    .  *
   *                                         *                                   *
   *                                         *                                   *
15 *    .0  58.2 4.5 11.4 20.1 5.3   .    .  *    .0 4.5   .0   .0 3.3   .    .  *
16 *    .0    .0  .0   .0   .0  .0 . .    .  *    .0  .0   .0   .0  .0   .    .  *
17 *    .0  59.6 4.4 12.5 18.8 4.5   .    .  *  10.1 4.5 71.9 56.9 2.8   .    .  *
18 *  83.0  58.0 4.5 13.1 24.3 4.7   .    .  *  43.3 4.4 20.4 36.1 3.2   .    .  *
19 * 100.0  71.6 4.7 11.6 19.6 5.8   .    .  *  55.7 4.4 18.2 28.2 5.3   .    .  *
20 * 100.0  69.2 4.7 11.4 20.0 5.7   .    .  *  49.4 4.5 20.4 31.3 5.4   .    .  *
21 * 100.0  70.3 4.8  9.5 20.0 5.8   .    .  *  46.5 4.5 19.2 33.0 5.4   .    .  *
22 * 100.0  72.9 4.7 11.5 20.0 6.4   .    .  *  41.2 4.5 25.2 38.0 5.2   .    .  *
   *                                         *                                   *
 AVE  60.3  57.5 4.0 10.1 17.9 4.8   .    .  *  30.8 3.9 21.9 27.9 3.8   .    .  *
   *                                         *                                   *
   *                                         *                                   *
 AVE  20.1  59.7 4.4 10.7 19.6 5.0   .    .  *  14.5 4.5  9.7 16.7 3.0   .    .  *
   *                                         *                                   *
----------------------------------------------------------------------------------
```

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Figure 11. Daily report for June 9, 1981.

(a) TREND KEY

LINE	COL 1	COL 2	COL 3	COL 4	COL 5	COL 6	COL 7	COL 8
TIME	FLOW gpm	SSR %	PHR pH UNITS	TPH	FERRIC PUMP CONTROL % SPAN	THICKNESS % SPAN	CAKE TONS % SPAN	CAKE TONS % SPAN SETPOINT
2	PHF pH UNITS	PHF % SPAN	PHF % SPAN SETPOINT	CSTF SECONDS	CSTF SECONDS SETPOINT	ORP mv	PF %	PL %
3	DRAFT PSIG	DRUM RPH	DRY VAC in Hg	VAT LEVEL % SPAN	VAT LEVEL % SPAN SETPOINT	PHL pH UNITS	FERRIC Q gpm	LIME Q gpm
4	HEARTH 2 °F	HEARTH 3 °F	HEARTH 4 °F	HEARTH 5 °F	OXYGEN %	HEARTH 3 BURNER % ON	HEARTH 5 BURNER % ON	RETURN AIR VALVE % OPEN

(b) TREND REPORT FOR JUNE 24, 1981

```
09:22:58    68.96     4.57     5.84     4.91    25.22    39.96    54.12    55.00
LINE2        6.37    84.40    50.71    36.78    35.71  -380.39    10.96    24.58
LINE3        -.23    10.04    11.83    32.00    30.00    11.99     2.14     9.71
LINE4     1029.31  1645.81  1717.37  1523.00    16.23      .00    93.64    18.60
09:28:12    67.34     4.59     5.84     4.53    24.59    35.44    48.66    55.00
LINE2        5.60    65.14    51.03    35.67    36.03  -337.07    11.03    20.68
LINE3        -.21    10.02    12.80    39.70    30.00    12.05     2.12     8.92
LINE4      997.65  1689.43  1736.12  1530.56    16.16    46.15    96.03    18.26
09:33:41    68.21     4.62     5.84     4.33    24.82    32.50    42.85    55.00
LINE2        5.52    63.15    51.35    36.05    36.35  -326.39    10.83    18.76
LINE3        -.21    10.03    12.92    46.32    30.00    12.00     2.13     8.31
LINE4     1010.00  1709.56  1763.31  1540.00    16.23      .00    97.45    18.60
09:38:51    68.48     4.66     5.84     4.41    25.24    33.27    42.85    55.00
LINE2        5.55    63.99    51.74    37.68    36.74  -306.39    10.82    20.03
LINE3        -.22    10.03    12.57    51.53    30.00    11.91     2.14     8.92
LINE4     1024.75  1696.75  1734.25  1546.62    14.88      .02    91.44    18.12
```

Figure 12. Example of trend report.

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D. CONTROL LOOP AND STRATEGY CAPABILITY

1. Output System

The RTUs are designed with three types of output interfaces, an electrically maintained contact closure, an electrically maintained but software timed contact closure, and finally a 10-bit resolution analog 4-20 ma or 10-50 ma continuous output.

The electrically maintained contact closure (relay) provides standard start-stop or open-close circuits for starting pumps and motors or opening valves and dampers. In the event of a failure of the RTU all contacts fail in the open position.

The timed contact closure has a timing range of 0.1 - 25 sec. The RTU receives a time value from the computer and then closes the corresponding contact for the specified time. This type of output is used for all increase/decrease controls. For example the vacuum filter drum drive is equipped with increase/decrease pushbuttons for controlling drum speed. In addition most incinerator damper controls use this type of control. The advantage of this method is that all devices hold last position in the event of any RTU or computer failure.

The analog output circuit represents the industry standard for continuous outputs and is used to regulate speed or position of devices. This type of circuit was used only where the existing equipment required it. In the event of failure of the RTU, the signal goes to zero and may stop or shut down devices causing a process upset. The three pumps supplying sludge to the vacuum filter are the only devices using this type of control.

2. Software Control Modules

Several control modules are provided in the system that essentially replace panel instrumentation and make control loop design more straightforward. An analog input module is included that provides for scaling, ranging, converting to engineering units, filtering, and storing of each individual input. Parameters can be entered and changed for each analog input module through the CRT console at any time. This module provides a way to calibrate each input at the CRT console based on field measurements. It also provides smoothing of noisy process signals.

A combined lead/lag module is available that provides these important control loop conditioning functions. The module operates either as a lead or as a lag module. In each case a time constant is adjustable from the CRT console to set the amount of lead or lag for a particular control signal.

A dead-time module is provided to delay a signal by an adjustable time. It functions as a storage file where sequential readings of an input signal are stored. The file is rotated, so that values are outputed after the deadtime has passed.

A linear compensator is provided that combines up to five input signals to form weighted average outputs. For each input a weighting factor must be included. The module then calculates the weighted average of the inputs assigned and scales the result to a 0 to 100 percent range. This module is particularly useful in feedforward-feedback control loops to combine the contributions and form one output.

A ratio controller provides a control signal based on flow signals. The base flow signal is multiplied by the operator entered ratio to produce the required secondary flow signal. If the secondary flow is monitored the module includes a PID section to maintain the secondary flow at setpoint using the feedback signal. If a feedback signal is not available the ratio module provides a calculation for a feedforward type control system.

A three mode proportional-integral-derivative (PID) controller module is included and provides the velocity form algorithm for feedback control of process variables. This module is designed with many options, such as error dead band and setpoint ramping, along with standard features, such as auto-manual, reverse acting, and deviation alarms. The module is provided in two forms, positioned and incremental; however, both forms use the velocity algorithm. Since all controller parameters are accessible from the CRT console and from other control modules or programs, many unique capabilities are available for adaptive control, control mode switching, and other strategy implementations.

There are no general calculation modules in the system except in the forms previously described; however, the process control language (PCL) permits FORTRAN like statements to be included in a control loop. This facilitates complex calculations using the PCL instead of using additional modules.

The output module provides an easy interface to the process outputs and, in particular, to the analog and incremental (timed) outputs connected to the RTUs. This module permits other modules and special loops configured in the PCL to make outputs to the process control devices via the RTUs. For each output, absolute limits and rate of change limits can be set to protect output devices and processes. The output module also functions as a manual loading station accessed from the CRT console.

3. Process Control Language (PCL)

A PCL is provided to facilitate control loop design and implementation. The language is designed to be used by process control engineers and not by programmers. It provides for the generation of additional control modules, access to all modules, and the implementation of complex control strategies involving several control modules and special calculations.

The language is in some ways similar to FORTRAN in terms of mathematical capabilities. The PCL provides the engineer with a repertoire of arithmetic and logical operations that can be applied to two data types, integer and floating point. The integer data type is primarily used for pointers, labels, counters, etc. The floating point data type is used for most calculations involving signals from the field to insure high resolution. Appropriate conversion rules are available to switch data types during a calculation if desired. Standard operators, such as addition, subtraction, multiplication, and division are provided and have string priorities similar to those used in

FORTRAN. Logical operations, such as AND, OR and exclusive OR are also available. Conditional branching using these operators is provided.

The PCL provides two types of subroutine calls. The call command is similar to the FORTRAN version. The SBRT command provides a way to execute program statements organized into a subroutine where those statements use the data (variables) that were in use prior to the command.

Data declarations are organized into two principle types, records and arrays. Records are blocks of structured data that can be configured into control module records or special records. Each record has an associated name and data type; and, has storage space for 16 integer values and 16 floating point values. In addition, each record can be scheduled for execution; and, program statements can be associated with the record.

Arrays are set up as three types, memory buffers, disc buffers, and history buffers (also on disc). Memory buffers are simply data tables that can be imbedded in the records and accessed by all control modules and PCL statements. Disc buffers are storage areas for data manipulation and long-term storage. The system programs provide all the necessary interfaces for reading and writing these arrays, so that they appear the same as a memory buffer to the control.

A scheduling mechanism is available to provide time based execution of all control programs. Each record (i.e. control module or strategy) can be scheduled to execute on a time basis or can be triggered as the result of another action in the system. A real time clock is maintained and is available to the control and reporting programs for time-of-day coordination.

Several formating, conversion, and printing functions are provided in the PCL for the generation of messages, printing of data and reports, and the generation of CRT displays. These features are used by the alarm and event message system to print events as they occur. Report and display programs may also use these features in combination with, or in addition to, the report generation system to print reports and set up displays on the CRT screen. These features create a high level of flexibility in designing application dependent reports and displays.

Finally, the PCL includes a full set of commands specially designed to provide an intimate and yet simple interface to all communication lines in the system. This permits the design of the RTU driver and other communications drivers to be done using the PCL directly.

E. OPERATIONAL DISPLAYS

The CRT console is equipped with three types of displays that enable the operator or engineer to monitor, control, calibrate, and test the system. They are menu displays, group displays, and point displays. Even though the display system is heirarchial in design, every display can be directly accessed if desired without going through other displays. This allows operators familiar with the system to go directly to the display desired. In general, for every display that contains live data, the live data are refreshed every five seconds.

Most point parameters that are set up once are not refreshed unless specifically so designated. Every display carries the system time and date which is also refreshed every five seconds.

The display organization is illustrated in Figure 13. The menu displays provide access information to the group displays. Each menu display is simply a list of group displays with their access information.

The group displays provide the primary mechanism for operator control of the process. Up to twenty group displays can be developed for each process area. Each of these displays access several inputs, control modules, and calculations in order to present a concise summary of the control strategy or of the process area.

The point display is the lowest level of the heirarchy and therefore presents the most detailed information. There is a display template (screen format) for each type of point or control module in the system. For example, the template for an analog input point will display the current value of the input in engineering units and in percent of range. It also gives all the parameters for the point, such as point name, range, zero and span, high and low alarm limits, alarm limit deadband, and smoothing filter constant. Every parameter is accessible to the operator through the CRT keyboard.

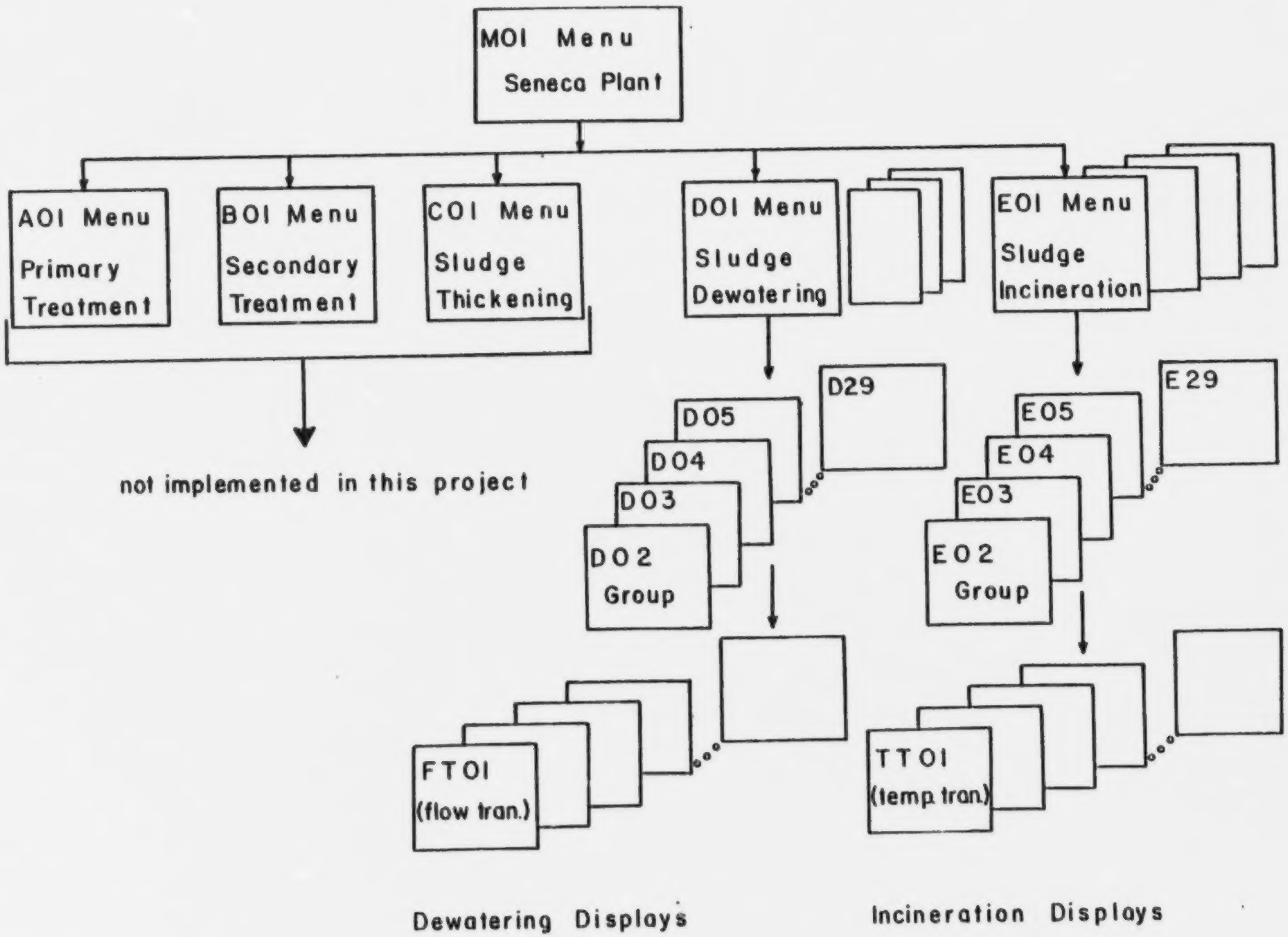

Figure 13. CRT display organization.

SECTION 9

ANALYTICAL METHODS

A. LABORATORY

1. General

Whenever possible the procedures presented in Standard Methods (10) were used to conduct the laboratory analyses. The procedures used to determine the rheological and dewatering characteristics of both the raw and conditioned sludge are presented in the following paragraphs.

The concentration of $Ca(OH)_2$ in the lime slurry used to condition the sludge prior to vacuum filtration was estimated from the specific gravity of the slurry. A plot of concentration vs specific gravity was developed using an acid titration method and a specific gravity hydrometer. The calibration curve was checked periodically to account for any variability in the quality of the lime delivered. A similar procedure was used for determining the $FeCl_3$ concentration.

2. Capillary Suction Time

Capillary suction time (CST) determinations were made with a Triton Type 92/1 CST Timer as described by Baskerville and Gale (11). All CST determinations were conducted with a 1.8 cm x 2.5 cm (diameter x height) cylinder. Whatman No. 17 chromatography paper was used as the absorbent medium. The CST apparatus is illustrated in Figure No. 14. When the cylinder is filled with slurry, water moves in the paper in a concentric pattern. An accurate measure of the rate of travel of the water is obtained by the timer which is activated and stopped when the water reaches the two probes. Triplicate determinations were performed on all samples; and, the average of the three determinations was reported as the CST of the sample.

3. Specific Resistance

The specific resistance, as presented by Gale (5), Vesilind (6), and others, is a measure of the ease with which water can be withdrawn from a thickened sludge. The test procedure consists of filtering a sludge sample through a filter medium mounted in a Buchner funnel and monitoring the filtrate volume as a function of time--see Figure 15. The vacuum applied to the filter assembly must be controlled or known. The specific resistance is defined as follows:

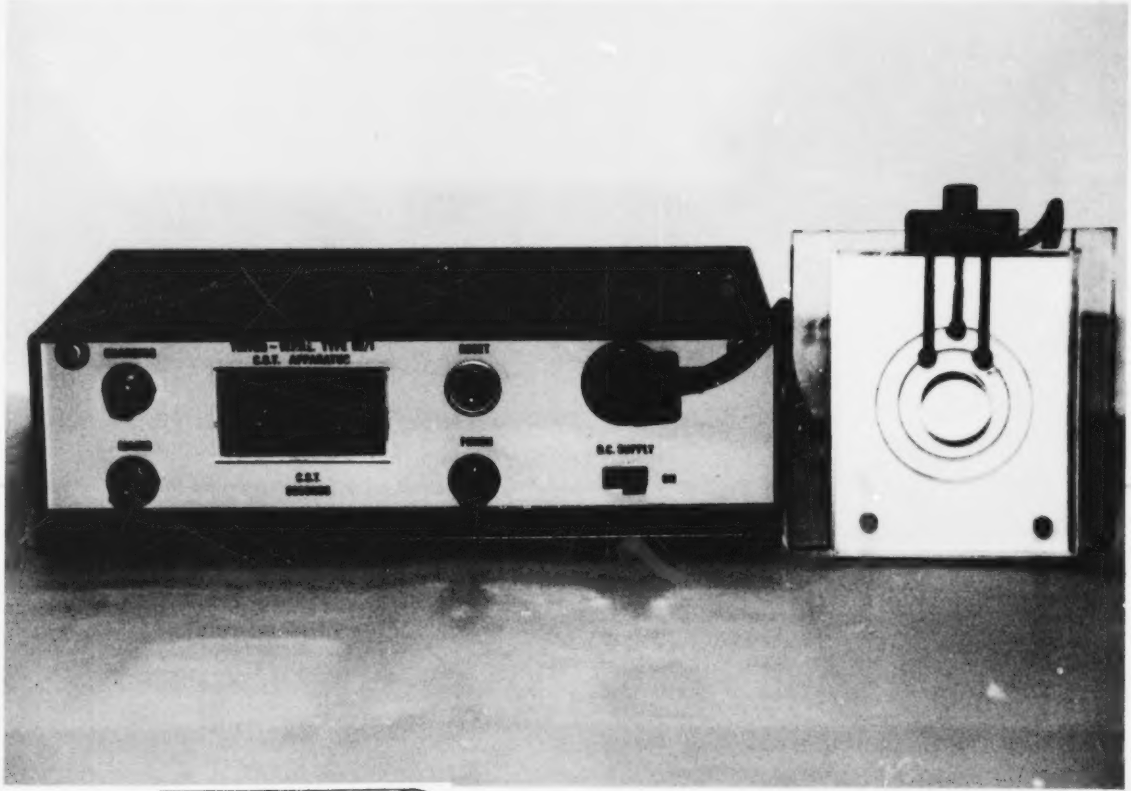

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Figure 14. CST apparatus.

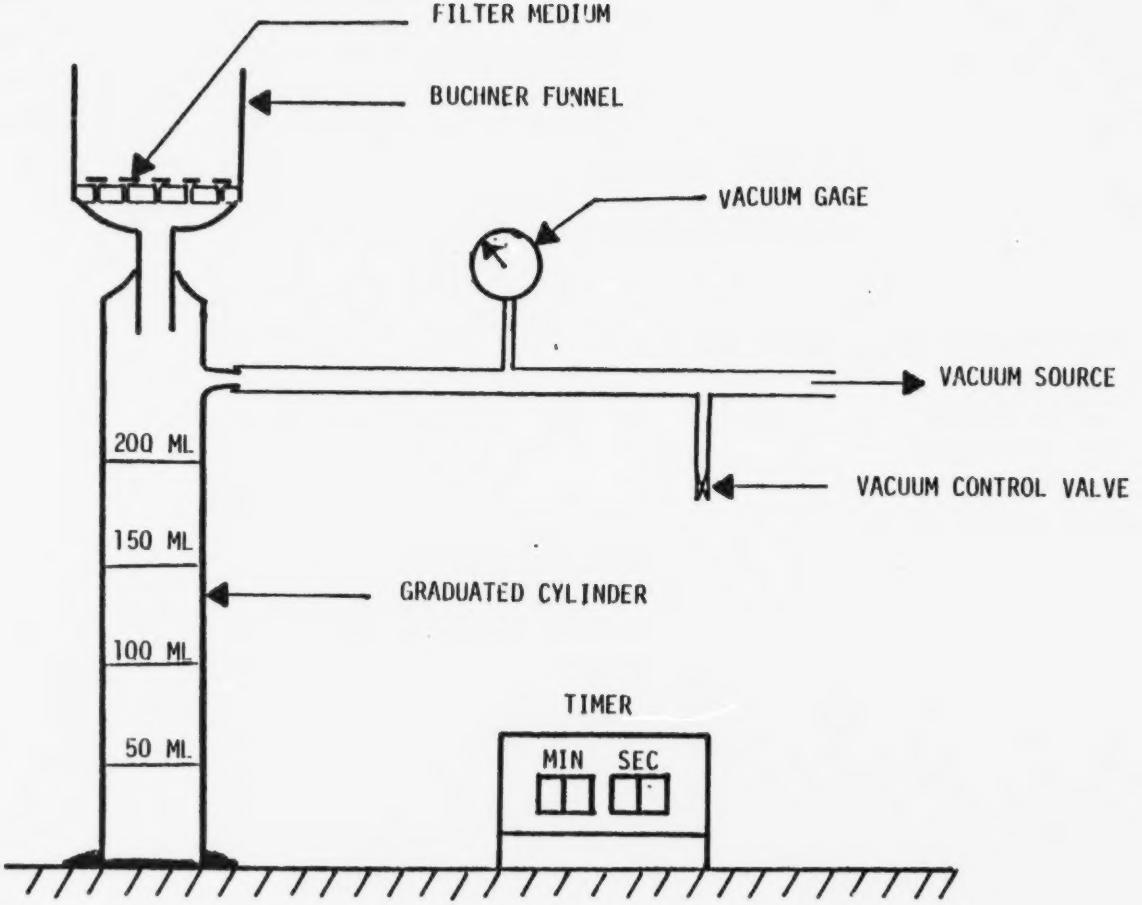


FIGURE 15. Apparatus for determining specific resistance.

[2] $$r_s = \frac{2bpa^2}{uW}$$

Where:
r_s = specific resistance - m/kg
b = slope of plot time/volume vs volume - sec/m^6
p = applied vacuum - N/m^2
a = filter area - m^2
u = filtrate viscosity - N sec/m^2
W = dry weight of cake divided by filtrate volume collected prior to onset of cake drying stage - kg/m^3

A circle of filter medium of the type currently installed on the Seneca vacuum filters was used and acid washed prior to each specific resistance determination. All tests were conducted using a 5.08×10^4 N/m^2 vacuum (15 in Hg).

The slope of the time/volume vs volume plot (b) was calculated from a linear regression analysis of the data prior to the onset of the cake drying stage of the filtration. The onset of drying was identified by a definite change in slope during the latter stage of the run. The viscosity (u) of the filtrate was assumed to be that of water at the measured temperature; because, viscosity determinations conducted on filtrate were not substantially different from the value for water.

Specific resistance determinations were made using sludge conditioned with both ferric chloride and lime. The filtration times encountered when using sludges conditioned with ferric chloride alone were excessive.

4. Viscosity

Chen and Hashimoto (12) demonstrated that the rheological properties of waste activated sludge (from a poultry waste treatment facility) could be described by a power law equation as follows.

[3] $$\tau = K\left[\frac{du}{dy}\right]^n$$

Where τ = shear stress

du/dy = velocity gradient or shear rate

K, n = constants

A Brookfield Model LVT rotational viscometer was used to collect rheological data. The spindle was rotated at eight speeds in the range of 0.3 to 60 RPM. The shear stresses and shear rates were calculated using the instrument readout and dimensional data supplied by Brookfield. The constants K and n are evaluated by plotting τ and du/dy on log-log paper and evaluating the slope and intercept. A typical plot of τ vs. du/dy is presented in Figure No. 16. As the plot indicates, there was some curvature at the low RPM values. To eliminate this problem, only the top five points were used to calculate regression lines.

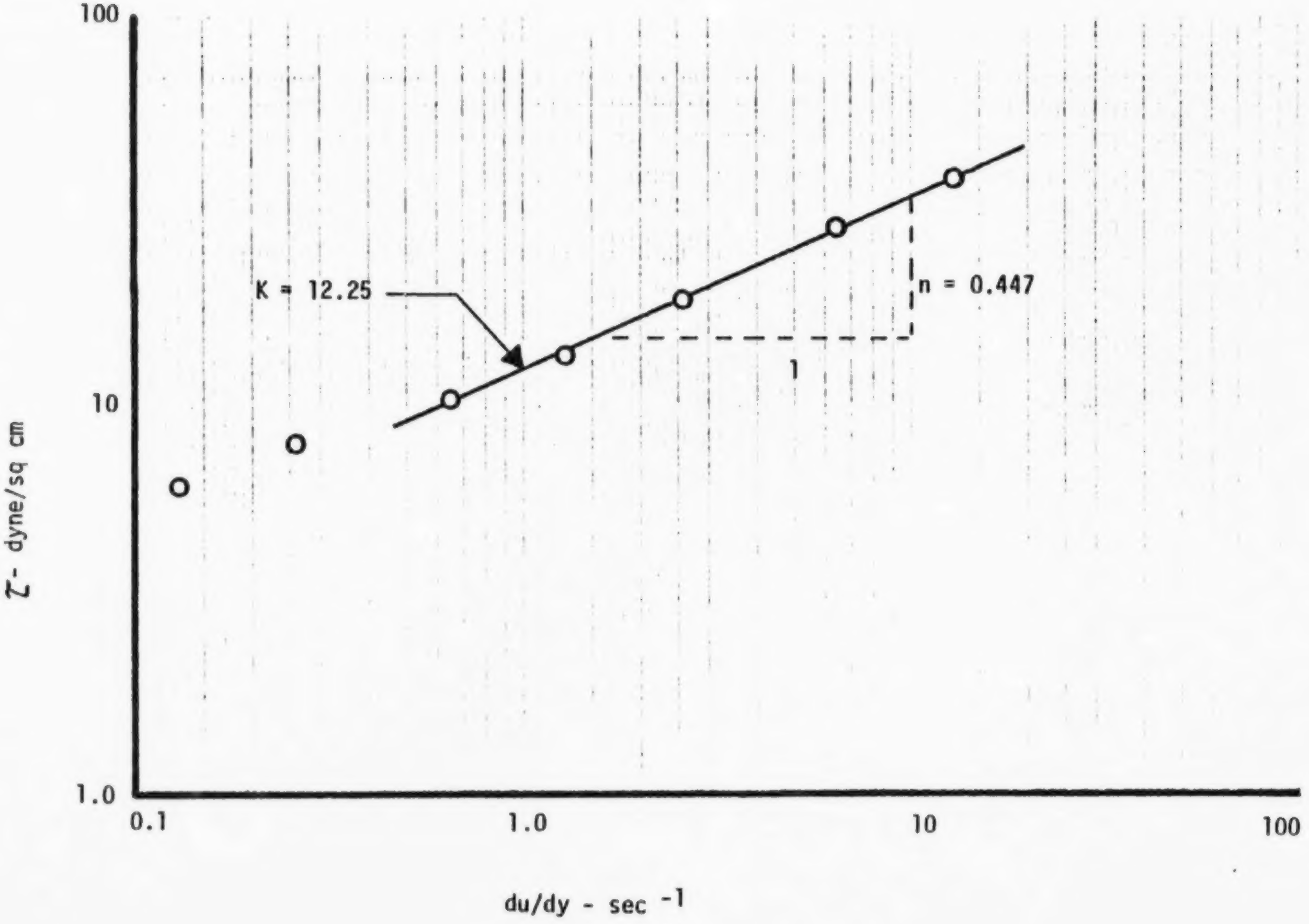


Figure 16. Typical plot of rheological data-Seneca raw sludge sample No. 1, 10/26/78.

B. FIELD CALIBRATIONS

1. General

Field calibrations were normally conducted on an intermittent basis between computer control runs and demonstration tests. Certain field instruments, however, were calibrated, or checked, just prior to and during controlled test runs. These calibrations included the belt scales, solids analyzers, chemical feed rates, lime sludge pH, and the flue gas oxygen analyzer. The incinerator thermocouples were calibrated only once because of the time required for each calibration.

Standardization of field instrumentation usually involved two calibrations. Initially the local instrument output was compared to field measurements or laboratory analyses; and, the computer generated output was subsequently compared to the local instrument output. All laboratory analyses and buffer solution preparations were conducted in accordance with Standard Methods (10).

2. pH

The pH electrodes were calibrated using two buffer solutions with pH values within the selected pH range. The instrument calibration adjustment was used to set the output to the lower pH buffer value. Subsequently, the instrument output was then set at the higher pH buffer value by adjusting the instrument slope control. The pH monitoring ranges were 4.0 - 8.0 for raw sludges, 3.0 - 7.0 for ferric chloride conditioned sludge, and 9.0 - 13.0 for lime conditioned sludge. The electrodes were removed from service, checked for coatings, and cleaned with dilute acid prior to calibration.

The calibration intervals for the raw sludge, ferric conditioned sludge and lime conditioned sludge monitors were approximately 2 weeks, 1 week and 2 days respectively.

3. Oxidation - Reduction Potential

The raw sludge ORP monitor was originally calibrated in the +100 to -300 mv range. Negative potentials exhibited by certain types of raw sludge required an adjustment in the range of -100 to -500 mv. A drifting electrode response and the lack of a stable reference solution prevented accurate calibrations in the negative mv region. A freshly prepared solution (5 ml of methanol containing 1 gram of dissolved quinhydrone diluted to 500 ml with 0.025 M-sodium carbonate; pH 11) was used to set the electrode response at -200 mv (versus Ag/AgCl) using the instrument calibration adjustment. Because of the lack of precision in the calibration procedure, adjustments in the instrument response were not made on a routine basis. The electrode was removed from service and cleaned approximately twice per month. Following cleaning and reinstallation approximately 24 hours were required for electrode equilibration.

The ferric chloride conditioned sludge ORP monitor was originally calibrated in the -200 to +200 mv range. The range was expanded to -500 to +500 mv to accommodate low solids sludges which produced more positive potentials following ferric chloride addition. Reference solutions described below were prepared prior to each calibration according to the manufacturers directions.

(1) 1 gram quinhydrone dissolved in 5 ml methanol; diluted to 500 ml with pH 6.86 buffer (potential: + 98 mv ±30 mv versus Ag/AgCl at 25C).

(2) 1 gram quinhydrone dissolved in 5 ml methanol; diluted to 500 ml with pH 9.18 buffer (potential: -32 mv ±30 mv versus Ag/AgCl at 25C).

An acid ferrous/ferric ion reference solution (+480 mv vs Ag/AgCl) was prepared according to ASTM method D 1498-76 (13) to check the electrode response at the positive end of the calibration range. The instrument calibration adjustment was used to set the output at +480 mv. The -32 mv reference solution was used to standardize the electrode in the negative mv region using the instrument slope adjustment. Calibrations of the ORP monitor were not conducted on a routine basis once the instrument calibration and slope adjustments were established. A drifting response exhibited by the electrode in the negative mv region prevented a more precise calibration.

4. Solids Analyzers

The solids analyzers used to monitor the raw sludge were zeroed against water when installed. The analyzers were calibrated while in service by collecting 5 grab samples from sample taps located approximately 3 m (10 ft) upstream of the analyzer installations. A concurrent meter reading was obtained for each grab sample. The average percent solids reading was compared to the measured total solids of a composite of the grab samples. If several consecutive calibrations demonstrated that a persistent deviation existed between the laboratory solids analysis and the instrument output, the instrument span adjustment was reset accordingly. The adjustment was not reset unless the deviation continuously exceeded 0.4% total solids. Analyzer calibrations were conducted approximately once per week. More frequent checks were performed if the sludge characteristics changed abruptly within the week.

5. Belt Scale

The belt scale used to monitor filter cake production was calibrated by sampling and weighing a known area of filter cake during two drum revolutions. At time zero the scale totalizer reading was recorded; and, immediately thereafter eight 15 cm (6 in) diameter samples were taken over the width of the filter media. The sampling procedure was conducted three times per drum revolution. Following the completion of the second drum revolution the final totalizer reading and the time were recorded. The cake area on the filter was determined by multiplying the width of the cake by the circumference of the drum. The cake weight was determined by multiplying the net sample weight per unit area by the filter cake area available in the two revolutions. The calculated cake production rate during the sampling period was determined by converting the calculated cake weight to tons and dividing by the total time in hours. The calculated production rate was compared to the average of the computer generated production rates recorded during the sampling period. If the production rates differed by more than 0.27 mt/hr (0.3 tons/hr) the computer generated rate was corrected to match the calculated rate.

A correction factor for the scale totalizer was determined based on the difference between the calculated cake weight and that indicated by the scale totalizer readings. Calibration procedures were identical for both filters. Scale calibrations were usually conducted several times per week due to the variability in cake loading on the belt and inconsistent belt tracking.

6. Oxygen Analyzer

Insitu calibrations were conducted using prepared gases (3.0% and 10.3% oxygen) and plant instrument air (20.9% oxygen). The 3% oxygen gas was used to make the low scale adjustment; and, instrument air was employed for span adjustments. The 10% oxygen gas was used as a midscale check. Calibration gas flow rates were maintained according to the manufacturers specifications. The gases entered the oxygen analysis cell through 0.6 cm (1/4 in) stainless steel tubing permanently installed on the analyzer. Calibrations were conducted prior to and during incinerator control tests.

7. Hearth Temperature

The temperature of each of the 7 hearths was determined from the measured mv output of each hearth thermocouple. The mv value was converted to a corresponding temperature from mv to temperature conversion tables supplied by the manufacturer. Each measured temperature was compared to the corresponding temperature (read to the nearest 5°C (10°F)) on the chart recorder located on the incinerator control panel. The average difference between the 7 recorded temperatures and the measured values was approximately 5°C (10°F). The maximum difference was 10°C (20°F) on hearth no. 7. Because of the close agreement between the measured and recorded temperatures, the temperatures displayed by the computer were adjusted to match those on the recorder prior to incinerator control tests.

8. Flow

a. Raw Sludge

The flow meters were calibrated by measuring the time required to fill the sludge conditioning tank when the sludge pumps were run at constant speed. The volume of the tank is 719 1 (190 gal.). A correction was made for the volume of ferric chloride solution and lime slurry discharged to the tank during the calibration period. The indicated flow rate was determined by recording the time required for the instrument totalizer to increase 757 1 (200 gal.). If the difference between the two flow rates exceeded 29 1/min (5 gpm) the flow rate displayed at the computer (indicated rate) was adjusted to match the measured value.

b. Ferric Chloride

Ferric chloride flow rates were determined by collecting and measuring the

the discharge volume of several pumping cycles at the sludge conditioning tank. After measuring the cycle time of the pump, the flow rate was calculated and compared to the flow rate indicated by the computer point display. The indicated flow rate was corrected at the computer to match the measured flow rate.

c. Lime

Lime flow rates were determined by collecting and measuring a lime pump discharge volume over a known time period at the conditioning tank. The volume measurements were repeated and the corresponding flow rates calculated at several pump speeds in order to establish a pump calibration curve. The lime flow rate indicated by the computer was calculated from the calibration curve for a given pump speed.

9. Vat Level

Vat level calibration was conducted by placing a circular target inside of the sensor baffle tube a measured distance from the sensor head. Instrument output (displayed on a chart recorder) was adjusted until the output signal corresponded to known target distances. On-line calibration checks were conducted by comparing manually measured vat levels with the instrument output generated on the computer trend report. Level corrections were made by resetting the computer analog input zero and span adjustments so that the instrument output corresponded to the measured level.

10. Drum Speed

Calibrations of the filter drum rotational speed were conducted concurrently with the belt scale calibrations using the time recorded for two revolutions of the drum. The recorded time was converted to rev/hr and compared to the drum speed indicated by the computer. Deviations exceeding 0.3 rev/hr were corrected in the computer drum speed point display.

SECTION 10

CHEMICAL CONDITIONING CONTROL

A. PRELIMINARY STUDIES

1. Chemical Feed and Mixing

The original plant design provided for the addition of ferric chloride to the raw sludge pipeline approximately 1 m (3 ft) upstream of the conditioning tank. The lime slurry was added in the conditioning tank. The close proximity of the ferric chloride addition point to the conditioning tank provided very little potential for mixing and completion of reactions. In addition, this arrangement prevented the application of monitoring and feedback instrumentation for evaluating on-line ferric chloride conditioning. In order to allow separate monitoring and evaluation of ferric chloride addition and to provide the required mixing for proper conditioning, a new feed line was installed to route the ferric chloride to the basement of the solids building just downstream from the raw sludge pumps. The new addition point provided approximately 38 m (125 ft) of in-line mixing prior to entering the sludge conditioning tank. No changes were made in the discharge location or mixing of the lime slurry.

The initial installation of the 7.6m^3 (2000 gal) ferric chloride day tank provided incomplete mixing of ferric chloride concentrate with water during the filling and dilution process. This resulted in the addition of high strength ferric chloride to the raw sludge which caused short term filter upsets. In order to minimize the effects of the ferric chloride dilution procedure, the frequency of the filling cycle was increased by initiating the dilution and mixing of concentrated ferric chloride whenever the level in the day tank reached the half-full position.

2. Physical and Chemical Characteristics

Chemical conditioning is used to alter the dewatering characteristics of sludges. In order to achieve control over this operation it is necessary to estimate or directly measure the dewatering characteristics of the sludge as a function of chemical addition. The two most commonly used methods of estimating sludge dewaterability for a vacuum filter are capillary suction time (CST) and specific resistance (SR). CST measurements have been related to the sludge solids concentration, the applied chemical dose, and the resulting pH.(4)(6) The specific resistance has been related to chemical dose, pH and CST (4), and vacuum filter performance (7).

Ideally, as the sludge dewatering characteristics change, an online measurement would produce a signal that could be used to vary the chemical dose so as to achieve the desired dewatering characteristics. Unfortunately neither CST or SR are directly measurable on-line; however, it was felt that a correlation was possible between other parameters, which could be measured on-line, and CST or SR or both. An analysis of previous laboratory data indicated that a reasonable correlation could be obtained between the CST of sludge conditioned with ferric chloride and parameters that could be measured on-line.

At about this same time a laboratory viscometer was used to collect the initial rheological data for raw sludge. These data yielded a high nonlinear correlation, 0.98, between the constant K, see equation [3], and the solids concentration. A moderate nonlinear multiple correlation, 0.89, between the dewaterability, as measured by CST, and pH and K was also observed. Based on these determinations, the decision was made to include rheological data in all further analyses.

During the period of November, 1978 through February, 1979, approximately 40 samples of raw, ferric conditioned, and lime conditioned sludge were collected for analyses. The feed rates of the conditioning chemicals were recorded at the time of sampling. Laboratory procedures were used to evaluate the parameters summarized in Table No. 1.

TABLE 1. SLUDGE DEWATERABILITY PARAMETERS

Symbol	Definition
SSR	Suspended solids concentration in raw sludge, % solids
PHR	pH of raw sludge
PHF	pH of ferric chloride conditioned sludge
PHL	pH of lime conditioned sludge
ORPR	ORP of raw sludge, mv
ORPF	ORP of ferric chloride conditioned sludge, mv
ORPL	ORP of lime conditioned sludge, mv
$\tau 12$	Shear stress of lime conditioned sludge, 12 RPM, dyne/sq. cm.
$\tau 30$	Shear stress of lime conditioned sludge, 30 RPM, dyne/sq. cm.
$\tau 60$	Shear stress of lime conditioned sludge, 60 RPM, dyne/sq. cm.
CSTR	CST of raw sludge, sec
CSTF	CST of ferric chloride conditioned sludge, sec
CSTL	CST of lime conditioned sludge, sec
SRL	Specific resistance of lime conditioned sludge x 10^{-11} m/kg
SSL	Suspended solids concentration in lime conditioned sludge, % solids
TL	Temperature of lime conditioned sludge, °C
PF	Ferric chloride feed, % by weight of dry sludge solids
PL	Lime feed, % by weight of dry sludge solids

The data were analyzed using the Statistical Package for the Social Science (SPSS) software (15) at the University of Minnesota Computer Center. The analyses yielded the following relationship for the specific resistance of the sludge after conditioning with ferric chloride and lime.

$$[4]\ \mathrm{SRL} = -5.9 + 0.76\ \mathrm{CSTL} - 1.52\ \mathrm{SSL} + 0.165\ \tau 60 - 0.098\ \tau 30 + 0.003\ \mathrm{ORPL} - 0.055\ \tau 12 + 0.83\ \mathrm{PHL} - 0.03\ \mathrm{TL}$$

The coefficient of multiple correlation was 0.85; however, the step-wise regression analysis indicated that essentially all of the useful information was incorporated into the model after the addition of the third variable.

Unfortunately, not all of the parameters in equation [4] are easy to monitor on-line. For example, CST cannot be monitored on-line and it is not feasible to measure shear stress at more than one rotational speed. When the ability to monitor parameters on a continuous basis was used as a constraint, equation [5] was found to be the best model of specific resistance.

$$[5]\ \mathrm{SRL} = 17.2 - 1.06\ \mathrm{SSL} + 3.41\ \mathrm{PHF} - 3.86\ \mathrm{PHR} + 0.006\ \mathrm{ORPF} + 0.1\ \mathrm{TL} - 0.45\ \mathrm{PHL} - 0.016\ \tau 30$$

Although the coefficient of multiple correlation dropped to 0.69, this preliminary analysis indicated the potential feasibility of constructing a workable sludge conditioning model from on-line data.

B. ON-LINE DATA

In order to verify or modify the relationships obtained using laboratory data, a number of monitors were installed in the chemical conditioning system to collect data on-line. Instruments designed to monitor suspended solids, pH, ORP, and viscosity were installed. With the exception of the viscometer, which did not appear to be sufficiently sensitive after it was screened to prevent debris from entering the chamber, all of the monitors yielded usable data.

During the period of September, 1979 through August, 1980, a total of 160 data sets were collected. These data are summarized in Table 2. The data collection procedures, which varied somewhat during the one-year period, are summarized as follows:

Raw sludge flow -- manual control through test 127, vat level control thereafter.
$FeCl_3$ feed -- manual control through test 127, pH control thereafter.
Lime feed -- manual control through test 127, pH control thereafter.
All pH and ORP -- manually recorded from monitor output through test 49, obtained from trend reports (average of 3 readings over 6-15 min) thereafter.

When the chemical feed rates, raw sludge flow rate, or the vat level setpoint were changed, sufficient time was allowed for the conditioning system and filter to equilibrate prior to collecting samples.

TABLE 2. SUMMARY OF ON-LINE CONDITIONING DATA

LINE	DATE 79/80	SSR	PHR	PHF	PHL	ORPR	ORPF	CSTF	SRL	PF	PL	TEMP	τ30
001	910	4.2	5.70	4.80	12.20	-340	70	19.7	1.35	12.0	56	27	6.7
002	910	4.2	5.70	5.10	12.20	-340	5	30.2	3.25	8.5	56	27	6.3
003	910	4.0	5.70	4.70	12.15	-338	70	19.1	1.30	15.0	72	29	5.7
004	910	4.2	5.70	4.75	12.15	-338	75	19.5	1.85	14.5	34	28	6.9
005	914	3.5	5.90	4.70	11.55	-312	150	13.3	3.20	15.0	21	25	5.7
006	914	3.4	5.90	4.80	9.80	-315	155	15.8	25.90	15.5	11	23	12.4
007	914	3.7	5.85	4.70	12.15	-315	185	14.9	1.65	16.0	26	24	6.3
008	914	3.6	5.85	5.50	12.25	-342	75	17.8	2.05	11.5	28	24	6.3
009	919	3.9	5.95	4.85	12.30	-420	50	14.3	1.15	16.0	47	26	6.1
010	919	3.8	6.00	5.35	12.30	-420	45	15.6	1.35	13.5	50	26	5.7
011	919	3.8	6.00	5.45	12.35	-420	35	15.4	1.50	11.5	39	26	6.1
012	919	3.8	6.00	5.70	12.35	-420	10	18.3	1.65	10.0	43	26	6.7
013	919	3.9	5.95	5.30	12.35	-420	50	16.6	1.50	10.5	38	26	6.2
014	919	3.9	5.95	5.45	12.35	-420	25	14.5	1.95	10.0	29	26	7.0
015	921	3.8	5.80	4.20	12.15	-338	195	14.9	0.85	22.0	41	27	6.9
016	921	3.7	5.80	5.05	12.30	-338	70	16.4	1.45	15.0	30	26	6.3
017	921	3.8	5.80	4.75	12.15	-338	100	14.9	1.30	18.0	24	26	6.7
018	921	3.8	5.80	4.70	11.90	-338	110	15.3	2.35	18.0	21	26	6.0
019	921	4.0	5.75	5.00	12.00	-338	75	16.5	2.45	11.0	20	26	6.8
020	925	3.7	5.90	5.30	12.40	-310	30	16.5	1.45	15.5	56	27	7.0
021	925	3.9	5.90	5.10	12.40	-310	55	15.9	1.50	17.0	53	27	7.9
022	925	3.8	5.90	5.20	12.40	-308	-12	18.3	2.30	14.5	46	27	8.0
023	925	3.9	5.90	5.35	12.40	-310	-30	23.7	2.10	12.0	45	27	8.4
024	926	3.8	5.85	4.80	12.20	-310	80	17.1	1.65	18.5	27	28	4.7
025	926	3.8	5.85	5.30	12.20	-315	40	19.4	1.95	16.0	22	28	6.8
026	926	3.8	5.85	5.40	11.95	-311	30	21.9	3.05	15.5	17	27	6.8
027	1002	3.8	5.90	5.40	12.20	-345	-125	26.4	2.80	10.0	21	27	9.1
028	1002	3.7	5.90	5.45	12.10	-345	-115	33.3	3.50	10.0	19	27	9.1
029	1004	4.2	6.10	5.90	12.30	-335	-60	56.0	5.60	6.3	18	27	8.1
030	1005	4.2	6.00	5.55	11.80	-340	-65	55.1	11.90	7.9	13	25	11.4
031	1005	4.3	5.95	5.60	12.25	-340	-80	58.5	5.70	7.7	19	26	10.8
032	1010	4.7	6.05	5.40	12.25	-348	-45	20.6	1.50	13.1	26	28	6.9
033	1010	4.6	6.05	5.60	12.20	-348	-40	34.1	2.85	10.7	13	27	9.5
034	1010	4.6	6.05	5.75	12.15	-350	-60	52.1	6.00	8.3	13	27	10.8
035	1016	4.9	6.10	5.15	12.20	-355	-5	25.5	1.30	13.0	23	27	6.2
036	1022	4.1	6.75	5.40	12.25	-370	-180	32.1	2.05	12.0	27	26	9.9
037	1022	4.0	6.70	5.30	12.20	-370	-140	28.1	1.75	14.0	26	26	7.1
038	1022	4.2	6.65	5.40	12.10	-370	-110	31.4	1.75	11.5	24	26	7.2
039	1022	4.2	6.65	5.45	12.00	-370	-100	31.3	2.70	11.5	22	26	9.1
040	1024	3.7	5.80	5.45	12.25	-350	25	34.0	2.50	8.5	27	26	7.6

TABLE 2. CONTINUED

LINE	DATE 79/80	SSR	PHR	PHF	PHL	ORPR	ORPF	CSTF	SRL	PF	PL	TEMP	τ30
041	1024	3.8	5.85	5.40	12.25	-345	-5	34.8	2.75	8.3	21	25	7.7
042	1024	3.7	5.80	5.55	12.25	-348	-30	38.9	4.05	7.8	18	25	9.9
043	1024	3.7	5.80	5.60	12.10	-349	-45	44.9	6.80	7.5	16	25	9.3
044	1026	3.2	6.30	5.10	12.35	-360	-5	20.1	1.35	17.0	50	27	5.7
045	1026	3.2	6.25	5.15	12.10	-351	5	23.4	3.95	15.0	18	25	6.3
046	1029	4.0	6.20	5.05	12.20	-355	-20	26.0	1.85	13.5	36	26	8.3
047	1029	4.0	6.15	5.35	12.20	-352	-50	27.5	2.50	11.5	34	26	8.5
048	1029	4.0	6.10	5.40	12.15	-342	-65	30.4	2.75	12.0	22	25	7.3
049	1029	4.1	6.10	5.60	12.10	-345	-100	40.0	3.30	10.5	14	25	7.9
050	1204	3.8	5.60	4.50	12.20	-340	-100	28.3	2.35	17.4	20	24	8.5
051	1205	5.4	6.20	6.05	12.20	-345	-118	36.9	1.25	13.7	23	23	-
052	1205	5.4	6.20	6.05	12.25	-345	-125	39.1	1.65	11.7	23	23	-
053	1205	5.4	6.00	5.90	11.90	-345	-105	48.5	1.50	8.4	16	23	-
054	1206	4.4	5.75	5.60	11.80	-325	-85	64.2	4.50	7.6	16	23	8.3
055	1206	4.4	5.75	5.60	12.30	-325	-92	63.4	2.60	6.6	20	23	7.5
056	1207	4.2	5.70	5.70	12.10	-340	-158	51.7	1.35	11.3	21	23	9.2
057	1207	4.2	5.80	5.60	12.30	-340	-160	54.1	2.05	9.8	21	23	7.5
058	1207	3.8	5.60	5.45	12.25	-340	-165	25.1	2.65	8.9	16	22	6.2
059	1207	3.8	5.65	5.65	11.50	-340	-152	40.7	5.40	8.5	14	22	8.4
060	1207	3.8	5.60	5.60	12.30	-340	-150	51.7	3.90	8.6	17	22	8.8
061	1212	3.3	5.90	5.65	12.40	-305	-55	21.3	2.60	8.3	39	23	11.0
062	1212	3.8	5.80	5.65	12.05	-305	-55	28.2	5.60	6.7	11	21	10.0
063	1212	3.7	5.90	5.30	12.15	-305	-35	34.4	4.10	8.1	21	21	11.8
064	1213	3.7	5.50	4.80	12.10	-295	92	30.4	2.25	9.2	26	22	10.9
065	1213	3.7	5.50	4.90	12.10	-295	50	36.1	4.10	7.7	21	22	12.6
066	208	4.6	7.50	5.65	-	-413	-20	34.3	-	6.6	-	-	-
067	208	4.4	7.48	5.73	-	-403	-20	33.5	-	8.1	-	-	-
068	208	4.7	7.47	5.84	-	-406	-40	41.5	-	8.3	-	-	-
069	208	4.7	6.96	5.86	-	-383	-60	55.2	-	6.9	-	-	-
070	208	4.3	7.45	5.91	-	-387	-80	33.5	-	7.7	-	-	-
071	208	4.3	7.45	5.92	-	-384	-80	37.7	-	7.6	-	-	-
072	208	4.4	7.43	5.95	-	-385	-90	43.7	-	8.2	-	-	-
073	211	4.9	6.59	6.05	-	-298	-60	38.6	-	8.0	-	-	-
074	211	4.0	6.60	4.73	-	-296	90	22.5	-	11.5	-	-	-
075	211	4.2	6.59	4.25	-	-302	140	23.5	-	11.6	-	-	-
076	211	4.2	6.63	5.38	-	-300	110	36.3	-	9.2	-	-	-
077	212	2.9	6.84	5.59	-	-383	68	21.0	-	9.5	-	-	-
078	212	3.1	6.81	5.41	-	-387	62	19.5	-	9.3	-	-	-
079	212	3.2	6.73	5.34	-	-389	50	22.5	-	8.8	-	-	-
080	212	3.0	6.84	5.39	-	-392	34	22.5	-	8.9	-	-	-

TABLE 2. CONTINUED

LINE	DATE 79/80	SSR	PHR	PHF	PHL	ORPR	ORPF	CSTF	SRL	PF	PL	TEMP	τ30
081	212	3.4	6.86	5.40	-	-395	20	20.0	-	7.9	-	-	-
082	212	3.4	6.83	5.42	-	-396	15	22.6	-	9.2	-	-	-
083	212	3.7	6.82	5.43	-	-397	8	21.8	-	8.6	-	-	-
084	212	3.7	6.81	5.40	-	-398	3	22.6	-	8.5	-	-	-
085	212	3.8	6.78	5.41	-	-391	-3	23.0	-	9.3	-	-	-
086	212	3.7	6.79	5.36	-	-396	-5	24.3	-	8.9	-	-	-
087	212	4.0	6.72	5.53	-	-400	-12	24.9	-	8.9	-	-	-
088	212	4.1	6.75	5.57	-	-400	-15	27.3	-	8.8	-	-	-
089	212	3.9	6.74	5.54	-	-399	-13	23.5	-	8.7	-	-	-
090	212	4.3	6.72	5.60	-	-401	-14	42.4	-	6.7	-	-	-
091	212	3.8	6.74	5.35	-	-403	-19	23.9	-	7.7	-	-	-
092	212	3.4	6.73	5.54	-	-403	-21	25.1	-	8.7	-	-	-
093	212	3.4	6.76	5.57	-	-403	-24	24.3	-	7.6	-	-	-
094	212	3.4	6.73	5.59	-	-402	-26	24.5	-	7.6	-	-	-
095	212	3.5	6.72	5.61	-	-406	5	22.5	-	10.5	-	-	-
096	212	4.3	6.66	5.61	-	-408	69	21.1	-	11.2	-	-	-
097	303	3.5	6.06	4.36	12.20	-176	322	34.0	1.20	8.2	40	19	-
098	303	3.5	6.04	4.34	12.20	-177	320	38.6	1.25	8.2	40	19	-
099	311	5.8	6.06	5.46	12.15	-352	185	35.1	1.60	6.9	18	19	-
100	311	5.0	6.18	5.28	12.20	-355	76	50.9	1.95	8.2	23	19	-
101	311	5.2	6.15	5.35	12.15	-355	52	29.1	1.90	8.0	22	19	-
102	311	5.1	6.22	4.92	12.15	-355	34	45.9	2.15	7.9	22	19	-
103	311	4.7	6.19	5.29	12.15	-355	15	39.1	2.50	8.7	27	19	-
104	311	5.0	6.21	5.31	12.15	-355	8	45.2	2.40	8.3	26	19	-
105	311	4.9	6.16	5.36	12.20	-355	2	39.2	2.45	8.7	25	19	-
106	311	5.0	6.17	5.37	12.20	-355	-4	28.2	2.60	8.4	25	19	-
107	311	5.0	6.16	5.36	12.10	-356	67	30.7	2.05	9.2	20	19	-
108	314	4.4	5.98	4.08	12.20	-359	368	19.0	2.80	7.3	19	19	-
109	314	4.3	5.96	3.66	12.20	-360	398	27.8	2.70	7.5	20	19	-
110	314	4.3	6.03	3.73	12.20	-359	373	18.3	2.60	7.5	20	19	-
111	314	4.2	6.01	3.71	12.20	-360	439	18.3	2.70	7.6	20	19	-
112	317	5.9	6.16	4.56	12.10	-354	339	27.2	1.45	5.7	14	17	-
113	318	5.2	6.03	5.13	12.20	-354	368	23.8	2.00	5.7	19	18	-
114	318	5.2	5.92	3.32	12.10	-354	452	19.6	2.10	5.5	19	18	-
115	318	5.3	5.92	3.42	12.10	-354	455	20.6	2.25	5.5	19	18	-
116	318	5.5	5.96	3.46	12.10	-353	446	21.5	1.85	5.3	18	18	-
117	318	4.4	5.90	3.60	12.20	-354	461	22.3	1.70	6.9	24	18	-
118	318	4.7	5.90	3.60	12.20	-349	500	-	1.65	6.9	24	18	-
119	318	4.8	5.95	3.65	12.20	-355	500	-	1.40	6.6	23	18	-
120	318	5.0	5.95	3.55	12.20	-351	500	-	1.55	6.0	21	18	-

TABLE 2. CONTINUED

LINE	DATE 79/80	SSR	PHR	PHF	PHL	ORPR	ORPF	CSTF	SRL	PF	PL	TEMP	τ30
121	320	4.5	5.88	4.08	12.25	-358	144	18.1	1.85	8.6	33	17	-
122	320	4.3	5.90	4.00	12.25	-356	410	15.8	1.70	7.5	37	17	-
123	320	4.2	5.92	3.92	12.25	-357	406	14.9	2.05	7.9	36	17	-
124	321	5.1	6.01	4.81	12.15	-334	274	31.9	2.45	5.7	16	17	-
125	321	4.7	5.98	4.88	12.20	-332	264	31.0	2.40	6.2	18	17	-
126	321	4.4	6.05	4.85	12.20	-338	265	22.3	2.45	6.6	16	17	-
127	321	4.3	6.06	4.56	12.15	-339	295	19.8	2.45	6.9	14	17	-
128	724	3.4	5.58	4.68	12.00	-330	165	-	2.10	15.7	24	20	-
129	724	3.4	5.69	5.29	11.98	-327	61	-	2.75	9.3	14	20	-
130	724	3.3	5.64	4.64	12.04	-327	113	-	2.50	15.0	22	20	-
131	724	3.4	6.07	5.27	11.85	-311	14	-	2.90	9.3	9	20	-
132	724	3.2	6.09	3.99	12.06	-307	226	-	2.15	19.6	34	20	-
133	724	3.3	6.11	4.81	11.95	-305	53	-	1.75	15.6	18	20	-
134	724	3.6	5.98	5.48	12.09	-279	18	-	2.35	8.0	14	20	-
135	724	3.6	5.90	4.70	11.78	-285	115	-	1.45	15.0	19	20	-
136	724	3.5	5.97	4.77	12.03	-267	58	-	1.55	14.1	22	20	-
137	729	3.3	6.00	4.70	12.14	-354	81	-	1.80	12.2	21	20	-
138	724	3.6	6.01	4.71	12.02	-274	96	-	1.50	13.1	20	20	-
139	729	3.2	6.02	4.72	11.95	-350	142	-	2.40	11.8	14	20	-
140	729	3.2	5.94	5.24	12.16	-337	38	-	3.15	9.3	18	20	-
141	729	3.5	6.10	5.30	12.16	-343	7	-	1.45	10.6	21	20	-
142	729	3.3	6.16	4.26	11.75	-355	130	-	2.20	13.5	13	20	-
143	729	3.5	6.12	4.02	12.00	-351	244	-	1.50	14.7	17	20	-
144	729	3.6	6.16	4.16	11.78	-347	143	-	2.55	13.5	15	20	-
145	729	3.2	5.94	4.24	12.07	-342	238	-	2.10	12.5	19	20	-
146	729	2.9	6.22	4.52	11.74	-351	214	-	2.75	12.1	13	20	-
147	729	3.1	6.21	4.71	12.04	-354	231	-	2.10	11.0	18	20	-
148	807	4.4	5.79	5.39	12.15	-374	-79	-	1.40	11.0	19	20	-
149	807	4.5	5.66	4.66	11.95	-358	95	-	1.10	13.0	15	20	-
150	807	4.2	5.71	4.91	12.00	-360	43	-	1.40	8.0	16	20	-
151	807	4.5	5.72	5.32	12.05	-384	11	-	1.55	8.0	18	20	-
152	808	4.5	5.78	5.48	11.89	-360	-88	-	3.45	7.0	10	20	-
153	808	4.5	5.72	5.22	11.95	-358	-38	-	1.35	9.0	14	20	-
154	808	4.5	5.70	4.70	12.01	-364	96	-	1.15	11.0	17	20	-
155	808	4.7	5.72	4.42	11.95	-353	159	-	1.05	14.0	20	20	-
156	808	4.6	5.71	4.91	11.79	-355	175	-	1.50	12.0	13	20	-
157	808	4.7	5.74	5.34	12.15	-364	51	-	1.30	12.0	31	20	-
158	808	4.6	5.75	5.45	12.11	-363	-8	-	3.10	8.0	12	20	-
159	808	4.6	6.02	5.12	12.00	-363	12	-	1.20	13.0	27	20	-
160	808	4.7	6.21	4.61	11.69	-362	150	-	1.10	16.0	20	20	-

Samples of the ferric conditioned sludge were collected from a tap just below the conditioning tank and the CST was determined immediately. The specific resistance was determined on the lime conditioned sludge immediately after the sample was collected from the conditioning tank overflow. The temperature of the lime conditioned sludge was determined with a laboratory thermometer and the rheological properties were determined with the laboratory viscometer at 30 RPM as outlined in Section 8. When it became apparent that the on-line viscometer would not function properly, the rheological data were no longer collected.

The conditioning data were collected to construct predictive models for both CSTF and SRL; and, the modeling effort was continuous during the data collection period. For these reasons not all data sets were complete.

C. MODEL DEVELOPMENT

1. General

The initial development of control strategies for the vacuum filter focused on methods for estimating sludge dewatering characteristics; because, it was assumed that the filter could be operated in a controlled manner to produce filter cake having a consistent quality if the sludge was conditioned to a predetermined level. If this goal was achievable automated control of the filter would be unnecessary as steady state conditions could be easily maintained. Since sludge conditioning, on an operating scale, is as much an art as science, the goal of this effort was to develop models that would be useful in control schemes designed to eliminate some of the variability in the dewatering characteristics knowing full well that control of the filter variables would also be required.

Since the conditioning process at Seneca uses both ferric chloride and lime, two control systems and hence two models were required. Since others (7) have demonstrated that the specific resistance adequately describes sludge dewatering characteristics for vacuum filtration, this parameter was chosen for study for the lime conditioned sludge. Initial attempts at determining the specific resistance of ferric conditioned sludge yielded extremely long filtration times and, in most cases, no cake was formed. Since the laboratory data demonstrated a strong relationship between SRL and CSTL, the CST of the ferric conditioned sludge (CSTF) was used to characterize the efficiency of ferric conditioning.

2. Capillary Suction Time

A total of 124 data sets collected over a 7-month period were used to construct the final CST predictive model. These data are summarized in Table 2. A number of relationships were developed during the data collection period to gauge the potential for success and the need for additional data. Multiple linear regression analysis techniques (15) were used to analyze the data. In addition, the significance of various interactions was determined along with squared and cubed terms. These modifications did not, in general, improve the goodness of fit.

The modeling efforts resulted in the following two equations for predicting the CST of ferric conditioned sludge.

$$[6]\quad \mathrm{CST1} = -3.0 - 0.099\,(\mathrm{ORPD}) + 8.4\,(\mathrm{SSR}) + 0.07\,(\mathrm{ORPF}) + 6.8\,(\mathrm{PHF}) - 2.0\,(\mathrm{PHD})$$

$$\text{coefficient of multiple correlation} = R = 0.70$$

$$[7]\quad \mathrm{CST2} = 66 - 0.104\,(\mathrm{ORPD}) - 1.8\,(\mathrm{PF}) + 6.0\,(\mathrm{SSR}) + 0.05\,(\mathrm{ORPF}) - 3.5\,(\mathrm{PHD})$$

$$\text{coefficient of multiple correlation} = R = 0.82$$

The two parameters, PHD and ORPD, are defined as follows:

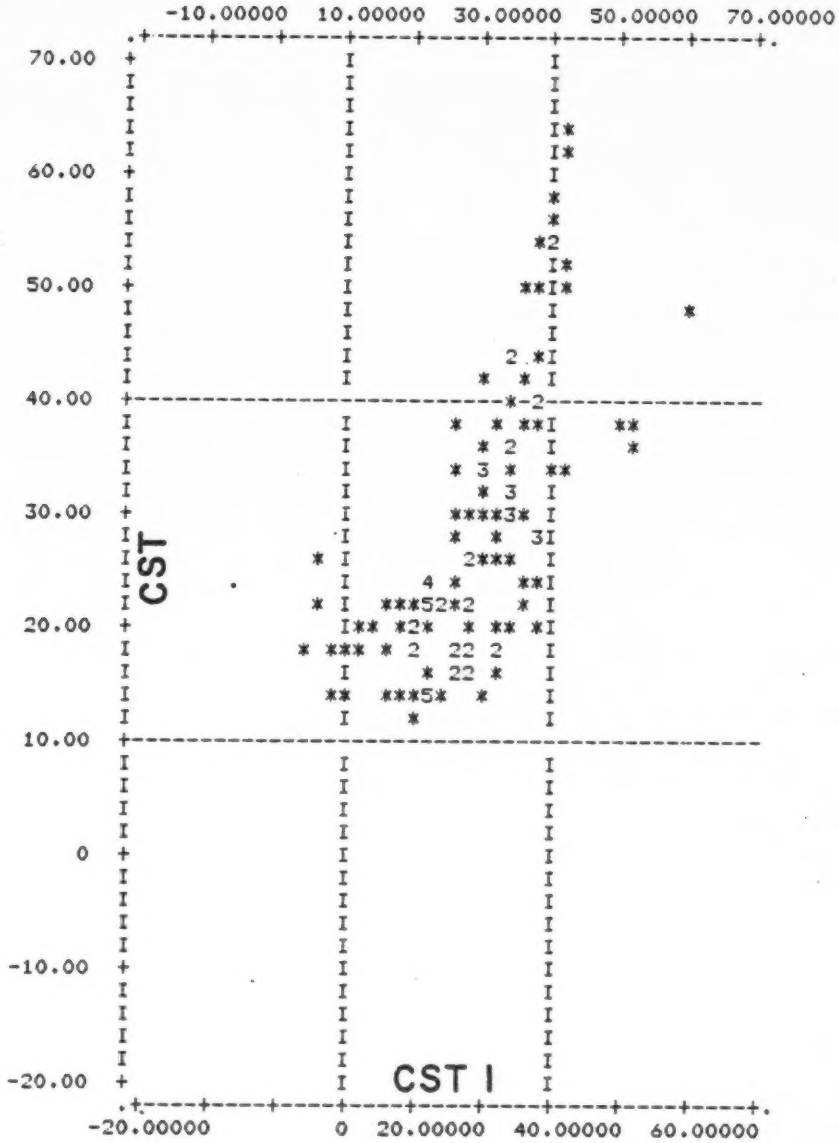
$$\mathrm{PHD} = \mathrm{PHR} - \mathrm{PHF} \quad , \quad \mathrm{ORPD} = |\,\mathrm{ORPR} - \mathrm{ORPF}\,|$$

The CST2 model, equation [7], contains a parameter, PF, which is directly affected by the control action; i.e., a change in the ferric chloride pump speed. The value of CST2 will respond instantaneously to changes in PF; however, the CST of the ferric conditioned sludge exhibits a response time of several minutes to step changes in PF. This lag is due primarily to the hydraulic residence time in the pipe between the point of ferric chloride addition and the sampling point. Because of this variable lag time, a model without the parameter PF was considered more desirable for process control purposes and CST1 was also developed.

The regression routine used (15) calculates a series of regression equations adding one additional independent variable in each step. The first independent variable entered is that exhibiting the highest simple correlation coefficient, r, with the dependent variable. The remaining independent variables which, when considered one at a time, yield the highest value of the coefficient of multiple correlation are added in step-wise fashion. The coefficient of multiple correlation, R, is determined for each step thus defining the significance of the independent variable added in any step.

Only the most significant independent variables were included for consideration when CST1 and CST2 were constructed. The data presented in TABLE 3 demonstrate that the addition of the last two variables did little to improve the goodness of fit. The value R^2, sometimes termed the coefficient of multiple determination, is in fact the ratio of the variation in the dependent variable, explained by the combined influence of the independent variables, to the total variation in the dependent variable. Thus, for models CST1 and CST2, 49% and 67% of the variability in the actual CST is explained by the independent variables. The variability not explained by the regression analysis may be related to the measurement precision of the field monitors; however, it is also likely that one or more important (but unknown) parameters were not monitored.

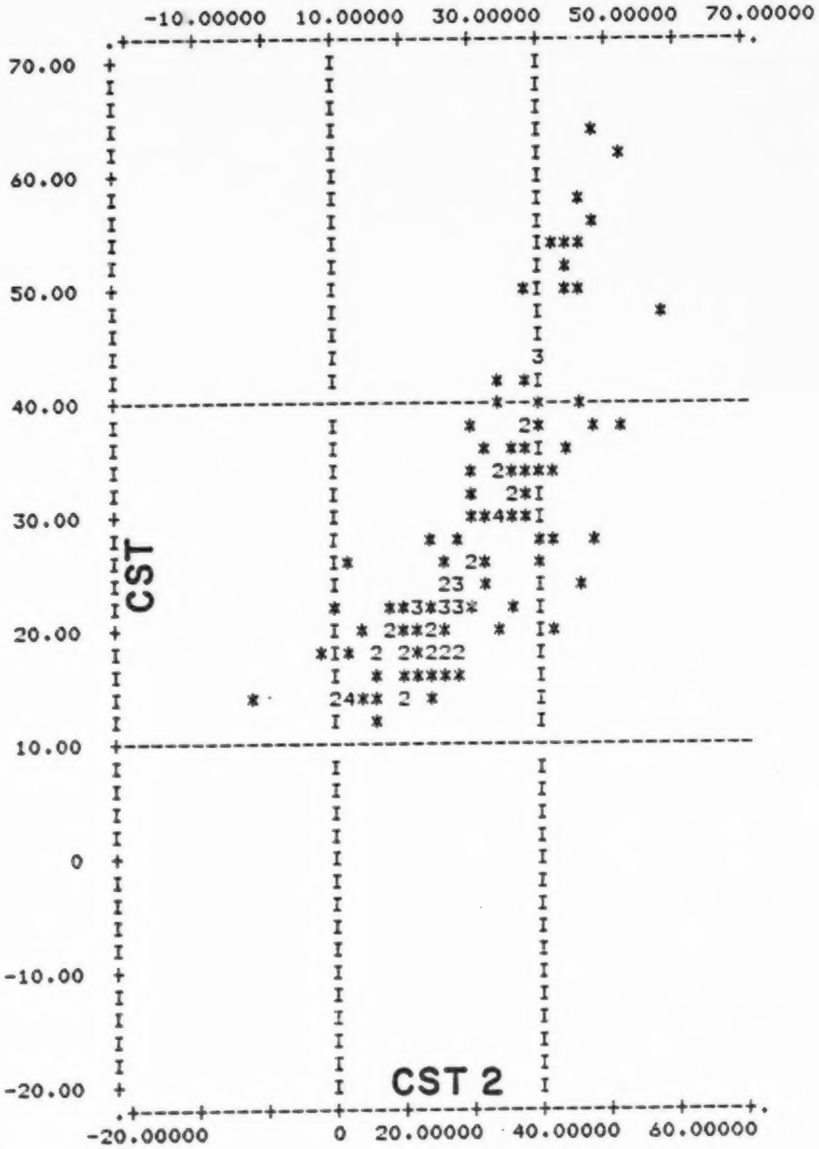
The goodness of fit for CST1 and CST2 is illustrated in Figures 17 and 18 for the 124 observations summarized in TABLE 2. Because of the better fit obtained with CST2, this model was selected for subsequent evaluation as the strategy for controlling ferric chloride addition.



```
CORRELATION (R)-         .68171  R SQUARED        -        .46473
SIGNIFICANCE R -         .00001  STD ERR OF EST -        8.70610
INTERCEPT (A)  -        5.68377  STD ERROR OF A -        2.38638
SIGNIFICANCE A -         .00939  SLOPE (B)        -        .81326
STD ERROR OF B -         .07902  SIGNIFICANCE B -          .00001

PLOTTED VALUES -      124
EXCLUDED VALUES-        0
MISSING VALUES -        0
```

Figure 17. Regression analysis for CST 1.



```
CORRELATION (R)-        .80362  R SQUARED          -          .64581
SIGNIFICANCE R -        .00001  STD ERR OF EST -             7.08199
INTERCEPT (A)  -       3.59589  STD ERROR OF A -             1.81116
SIGNIFICANCE A -        .02467  SLOPE (B)          -          .85011
STD ERROR OF B -        .05700  SIGNIFICANCE B -              .00001

PLOTTED VALUES -        124
EXCLUDED VALUES-          0
MISSING VALUES -          0
```

Figure 18. Regression analysis for CST 2.

TABLE 3. REGRESSION SUMMARY FOR CST1 and CST2

Step	Variable Entered	Individual r	Cumulative R^2
CST1 - 1	ORPD	-0.49	0.24
2	SSR	0.35	0.45
3	ORPF	-0.44	0.46
4	PHF	0.46	0.48
5	PHD	-0.39	0.49
CST2 - 1	ORPD	-0.49	0.24
2	PF	-0.42	0.55
3	SSR	0.35	0.64
4	ORPF	-0.44	0.67
5	PHD	-0.39	0.67

3. Specific Resistance

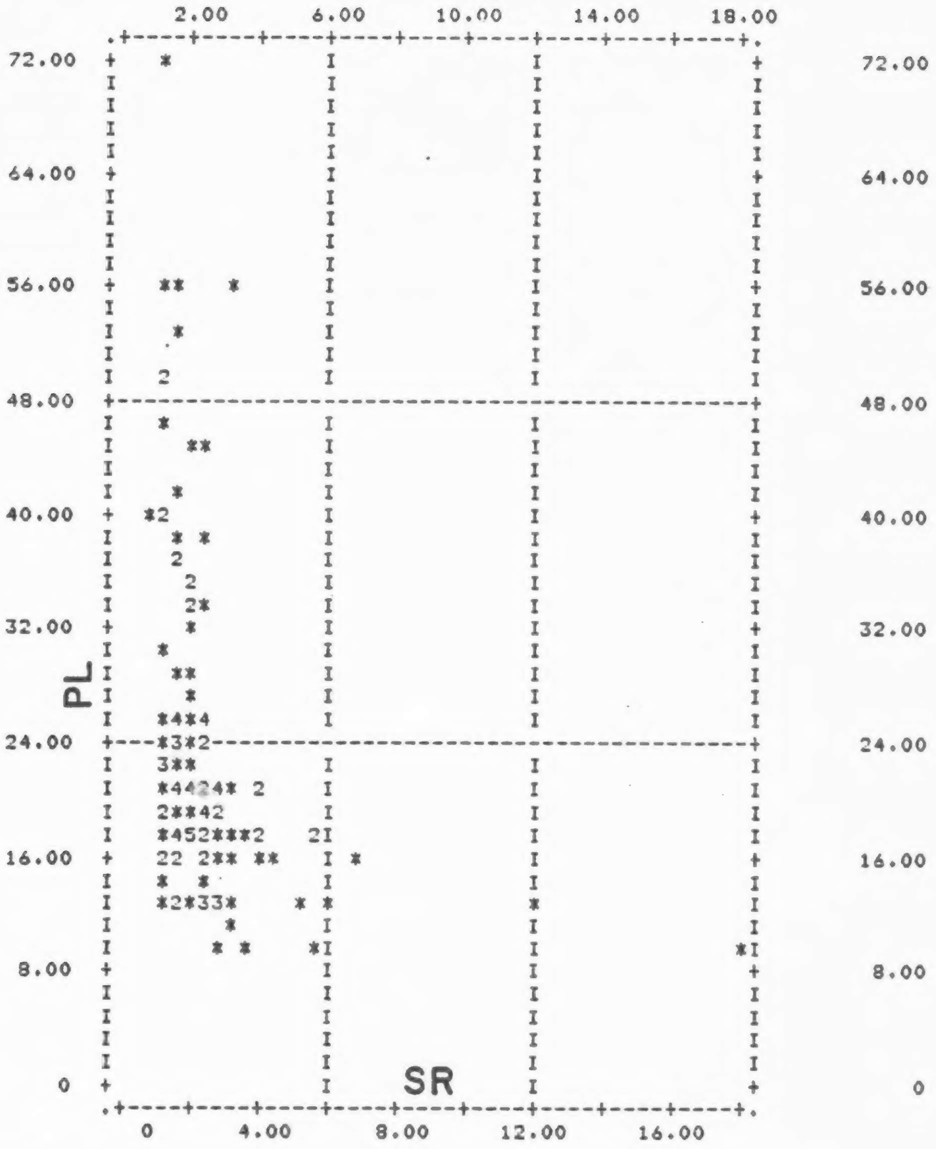
The modeling effort for specific resistance was conducted concurrently with the CST work. A total of 129 data sets were collected over a 12-month period as summarized in TABLE 2. Although the data were collected using on-line instrumentation, prior to July, 1980 the sludge conditioning process was controlled manually by the operator; and, the chemical dosages reported in TABLE 2 reflect the natural tendency to be conservative and overdose. This is particularly true for the lime addition. This may be due to the fact that problems with cake release, (from the cloth) are less likely with higher lime dosages; and, the lime pumps could be adjusted in the filter control room; whereas, the ferric chloride pumps could be adjusted only at the pump, three floors down. Regardless of the cause, a review of the data in TABLE 2 indicate that the lime dose was extremely variable and often well above the range of 15-25% typical at other MWCC facilities using vacuum filters.

The data in Figure 19 illustrate the impact of excessive lime dose. Although this is a simplistic approach, increasing the lime dose above approximately 30% does not appear to affect a change in specific resistance; and, these data were thus eliminated from consideration in the modeling efforts. In addition, two additional data sets were eliminated because the value of SRL was extremely high (>10); and, in fact, the filter failed to produce cake on those two occasions.

The edited data base consisted of 103 observations. The regression technique previously discussed was used to generate two equations, SR1 and SR2, as follows:

$$[8]\ SR1 = 19.9 - 0.19\ PHD - 0.22\ PF - 0.73\ SSR - 0.0020\ ORPD - 0.93\ PHL$$

coefficient of multiple correlation = R = 0.66



```
STATISTICS..

    CORRELATION (R)-        -.30802      R SQUARED        -        .09487
    SIGNIFICANCE R -         .00019      STD ERR OF EST -        10.65032
    INTERCEPT (A)  -       28.53929      STD ERROR OF A -         1.52757
    SIGNIFICANCE A -         .00001      SLOPE (B)        -       -1.76812
    STD ERROR OF B -         .48461      SIGNIFICANCE B -          .00019

PLOTTED VALUES -   129    EXCLUDED VALUES -     0   MISSING  VALUES -     0
```

Figure 19. Relationship between PL and SR.

$$[9]\ SR2 = 12.0 - 0.04\ PL - 0.19\ PF - 0.68\ SSR - 0.16\ PHD - 0.25\ PHL - 0.002\ ORPD$$

coefficient of multiple correlation = R = 0.68

The inclusion of the lime dose, PL, in SR2 did not significantly increase the overall goodness of fit. In both instances, less than 50% of the variability in the specific resistance was accounted for; and, the equations are thus not adequate models for the control of specific resistance.

D. CONTROL STRATEGY DEVELOPMENT AND EVALUATION

1. Ferric Chloride Feed

a. General

A number of control schemes were considered for the control of the ferric chloride addition as follows (in order of increasing complexity): (a) constant dose based on volume, (b) constant dose based on sludge solids, (c) constant pH or ORP, (d) constant Δ pH(PHD) or Δ ORP(ORPD), (e) variable Δ pH(PHD) based on raw solids concentration, and (f) CST control based on CST model. Although schemes (a) through (d) would be relatively simple to implement and maintain, they do not respond to the change in the physical and chemical characteristics of the raw sludge experienced at Seneca and thus result in periodic over and under dosing. If the sludge characteristics were relatively constant, manual control of the entire solids processing train would be sufficient. The development and evaluation efforts were thus limited to options (e) and (f).

b. pH Control

Ferric chloride is a salt of a strong acid and, as such, decreases the pH of raw sludge by a significant amount for the dosage range normally used. The first method proposed for control of the ferric chloride addition was based on pH. This method was proposed because it is simple and pH is relatively easy to monitor. Batch tests conducted in 1976, summarized in TABLE 4, demonstrated that sludges with poor filtering characteristics, as measured by CST, generally have a lower pH, less negative redox potential, and a lower solids content. Visual observations also indicated that the average particle size was smaller in the sludges with higher CST.

Since the addition of significant quantities of $FeCl_3$ to the raw sludge produces a measurable increase in the ORP along with a decrease in pH, both variables were used to design simple feedback control schemes. The dynamic characteristics for both the pH and ORP control loops were determined simultaneously. The tests demonstrated that both the pH and ORP monitors responded to a change in the ferric chloride pump speed. The pH signal was observed to contain much more noise than the ORP signal. The frequency of the pH noise appeared to correspond to the stroke rate of the ferric pump, which indicates that mixing was not complete in the sludge line. The ferric chloride may have remained in pockets in the sludge line at regular intervals thereby causing the signal "noise." The ORP signal was relatively smooth.

TABLE 4. SLUDGE PHYSICAL, CHEMICAL, AND DEWATERING CHARACTERISTICS

Sludge Type	pH	ORP mv	CST sec	Solids %
Fresh mixed *	6.0	-200	225	3.2
Aged 10 days	5.7	-	345	2.7
Fresh	6.05	-150	190	4.2
Poor filtering	5.5	-100	290	3.3
Fresh mixed *	5.95	-225	255	4.5
Aged 3 days	5.4	-195	325	-
Aged 4 days	5.4	-150	-	4.1
Aged 6 days	5.4	-110	470	4.1

* Primary and waste activated sludges

The ferric tests summarized in TABLE 5 indicate that the time before response (dead time) of the pH and ORP are about the same; however, the process storage time (time to reach 63% of final value) for the pH signal is much shorter than for ORP. Since the pH signal would require a filter (which introduces a delay), the pH and ORP signals are essentially equivalent dynamically in their advantages and disadvantages for use as feedback in the control.

The analyses of the $FeCl_3$ testing provides the prerequisite data to construct a dynamic model for pH control of the process. A block diagram of this model is illustrated in Figure 20. The model is expressed in Laplace transform notation for control system convenience. The model indicates that a change of 3.8 l/min (1 gpm) in pump speed multiplied by the process gain of -0.89 would result in a pH change of -0.89 after a sufficient time was elapsed. The deadtime and lag times (dead time plus lag time = storage time) appear as coefficients of the Laplace variable S. Using this dynamic process model the theoretical gains for the PID three mode controller where calculated.

Even with a closed loop pH control running, it became apparent that there was no universal pH setpoint that the control loop could use to maintain the dewatering characteristics relatively constant. Thus the feedback approach, even through variations in pumping and in ferric chloride concentrations were now eliminated, required additional parameters to make the loop functional and responsive to the real sludge conditioning needs.

Previous experience with sludge conditioning demonstrated that the ferric chloride dose (based on dry solids) required for successful vacuum filtration increased as the solids concentration in the raw sludge decreased. In order to reflect the change of this physical characteristic of the raw sludge the control scheme was modified to calculate and maintain a value of Δ pH (PHD) based on the solids concentration of the raw sludge as follows:

TABLE 5. PROCESS DYNAMICS $FeCl_3$ CONDITIONING

Date	Time	Chart	Pump change	pH			ORP		
				K	DT	TPS	K	DT	TPS
1980			l/min (gpm)	process gain	dead time (min)	storage time (min)	process gain	(min)	(min)
9-19	11:30	A	9.8 (2.6)	-1.00	1.5	2.0	-1.10	1.4	3.2
9-19	13:50	B	9.1 (2.4)	-0.74	1.8	2.3	-0.72	1.2	3.4
9-19	14:27	C	10.2 (2.7)	-0.80	1.0	2.2	-0.70	1.4	4.7
9-21	15:14	D	10.2 (2.7)	-1.03	1.3	1.8	-1.29	1.3	3.6
			Averages	-0.89	1.3	2.1	-0.95	1.3	3.7

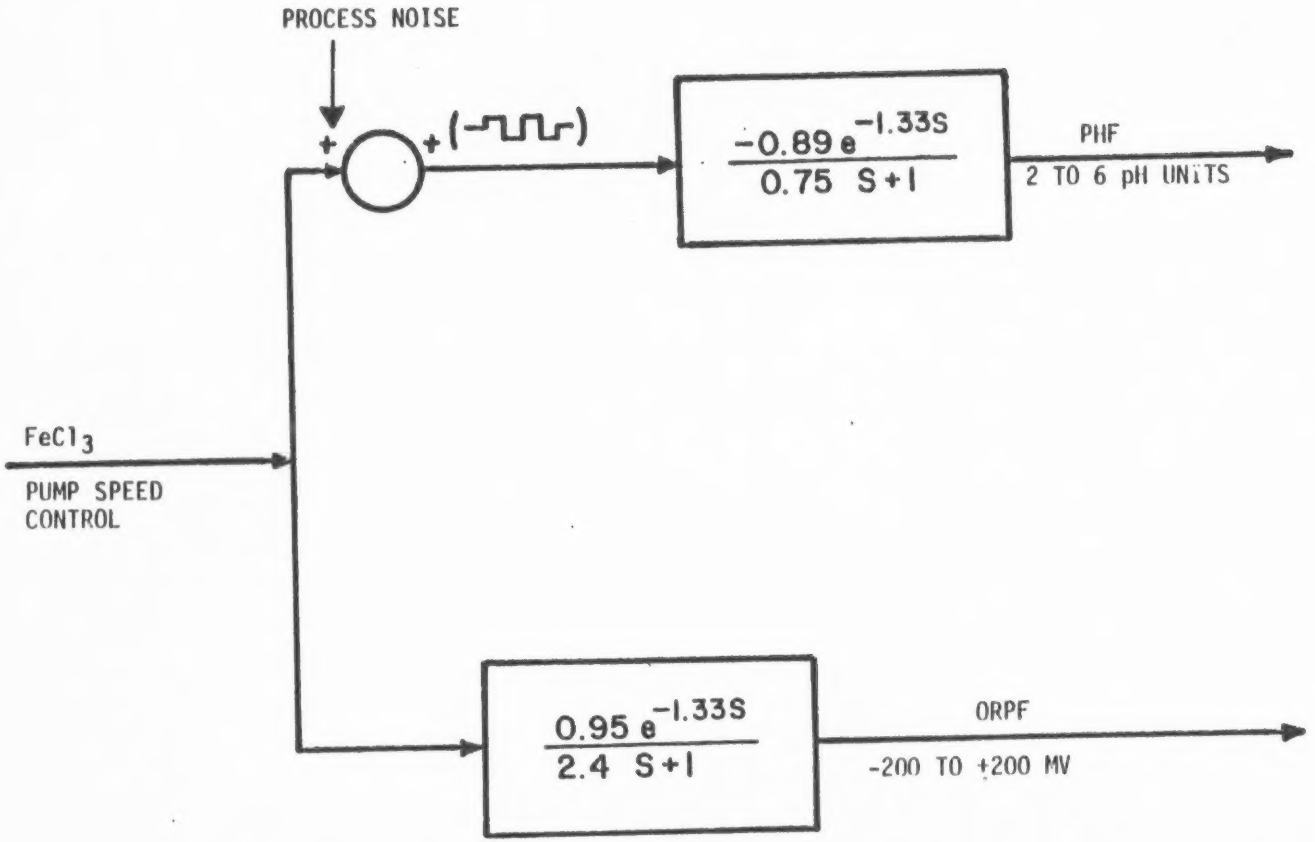


Figure 20. Dynamic model for $FeCl_3$ effect on pH and ORP of sludge.

$$[10]\ \text{PHD Setpoint} = K_2 - K_1\ (\text{SSR})$$

and

$$[11]\ \text{PHF Setpoint} = \text{PHR} - \text{PHD Setpoint}$$

The results of four tests conducted during October, 1980; summarized in Figure 21, demonstrate that the control system could provide reasonable control of PHF; however, deviation from setpoint did occur. Some of the deviations below setpoint were, no doubt, caused by pumping higher strength ferric chloride solution during the fill cycle of the ferric chloride day tank. The deviations not withstanding, the ability to maintain PHF at the setpoint does not insure proper conditioning unless the setpoint value is appropriate.

The default values chosen for K_1 and K_2 were 0.5 and 3.0 respectively. Using these values a reasonable $FeCl_3$ dose was obtained a large percentage of the time; however, over and under dosing did result when characteristics of the raw sludge (other than SSR) changed. This required that new values for the constants be entered into the control software. The control system was thus reduced to a semi-automated scheme requiring periodic judgement by the operators.

Applications of the pH control strategy relied heavily on the continuous operation of the pH monitors. Under such conditions the pH electrodes require the periodic attention of the operator to assure a reasonable response time.

c. CST Control

After it was demonstrated that the CST was the only practical method available for characterizing the dewatering characteristics of sludge after addition of ferric chloride, it was assumed that a control system capable of maintaining the CST within a relatively narrow deadband, around the setpoint, would compensate for the normal changes in sludge quality. The development of a model relating the CST of the ferric conditioned sludge to the measurable sludge parameters was presented earlier in this Section. The use of the model in the design of the control strategy is illustrated in Figure 22. A cascade control is used to adjust the ferric pump. The inner loop controls the pH of ferric conditioned sludge by adjusting pump speed. The pH setpoint is generated by a CST controller. If the CST is below setpoint (over-conditioned), the pH setpoint is increased; and, if the CST is above setpoint the pH setpoint is decreased. The pH feedback loop was retained because of its advantages of (a) providing corrective action on errors, (b) eliminating pump metering fluctuations, and (c) eliminating fluctuations caused by ferric chloride concentration changes.

The model receives inputs from the process sensors and calculates a predicted conditioned sludge CST value. This prediction is then compared to the desired CST setpoint. If they are different an adjustment is calculated for the pH controller's setpoint which ultimately will change the CST to its desired value. To avoid coupling problems the control part of the CST model is designed to be recalculated very infrequently relative to the pH controller, thereby appearing to be constant to the controller. The control strategy flow chart is presented in Figure 23.

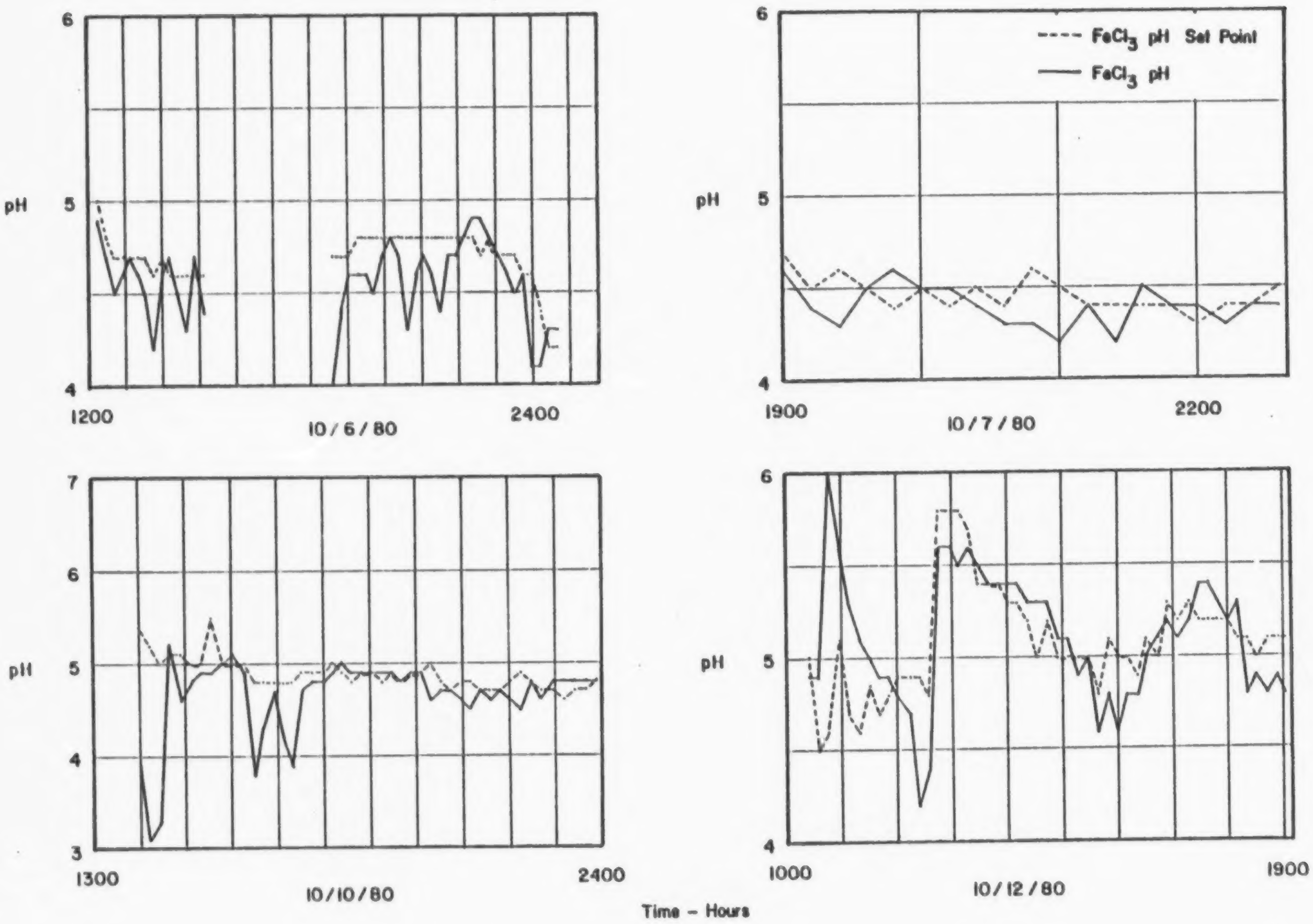


Figure 21. pH control using the Δ pH strategy for $FeCl_3$ addition.

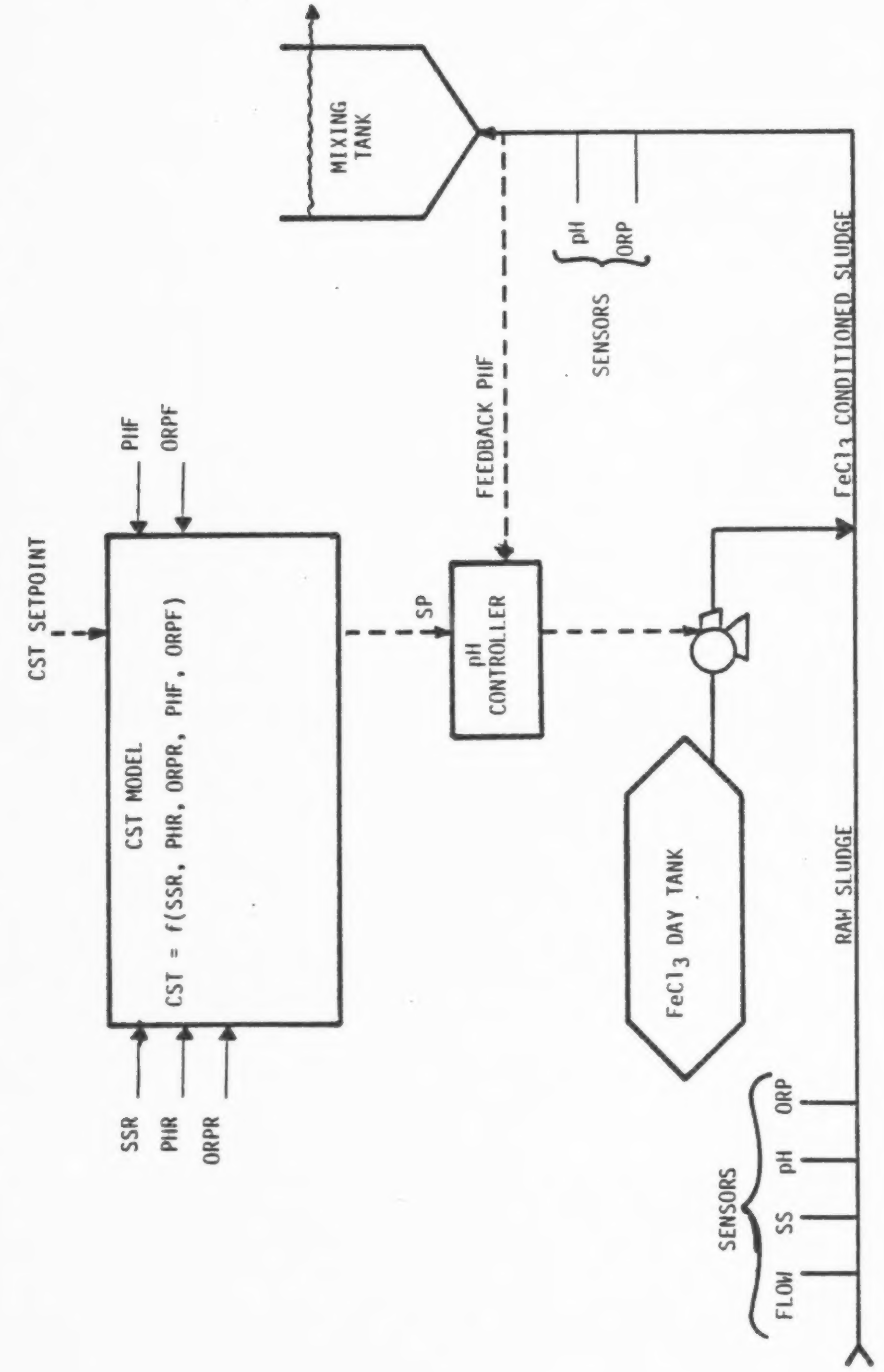


Figure 22. Ferric chloride dose control based on CST.

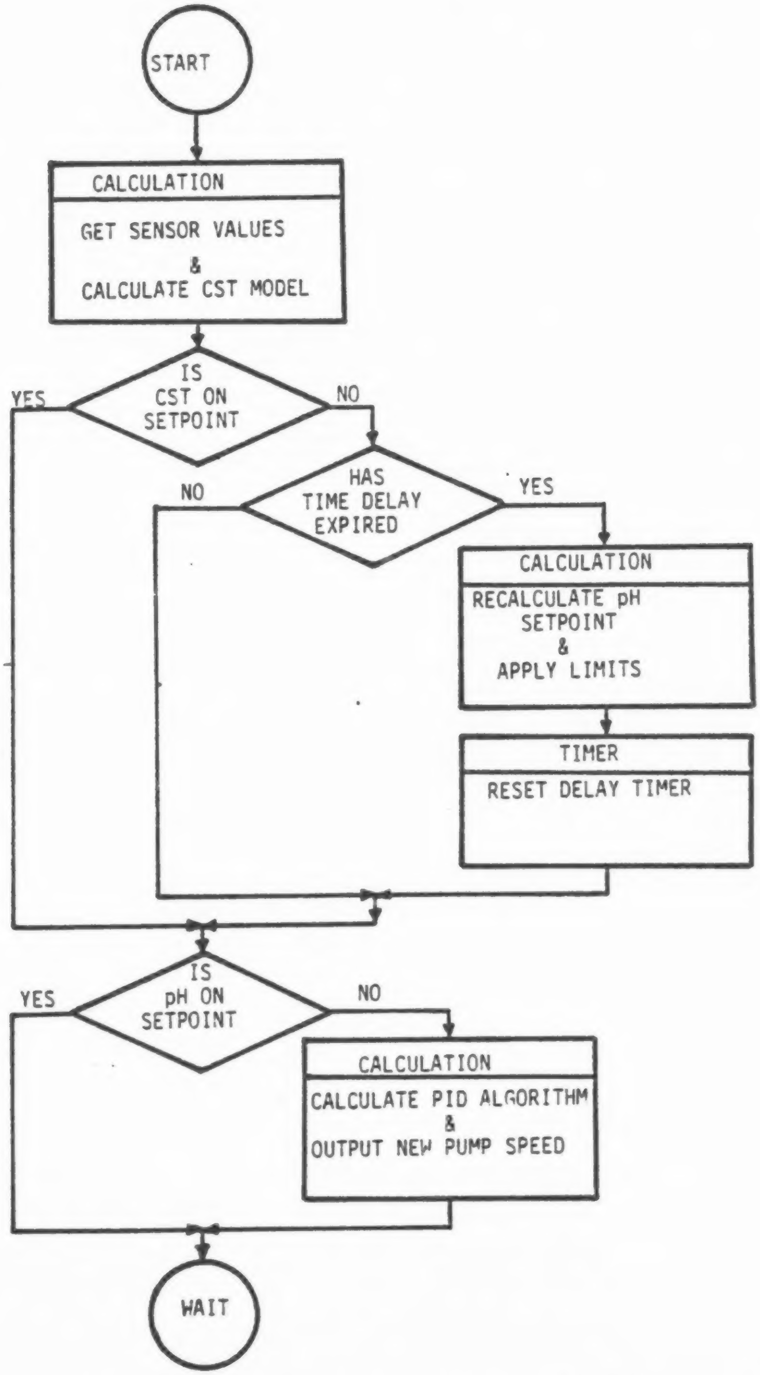


Figure 23. CST control strategy flow chart.

On-line CST control began in September, 1980 using the CST 1 model to calculate a CST value. A constant CST setpoint, used initially, proved to be unworkable because the ferric chloride pump would be ramped to maximum or minimum speed if the CST setpoint could not be attained. A variable CST setpoint calculation was initiated based on the raw sludge solids as follows:

[12] $$\text{CST setpoint} = K_3\ (\text{SSR}) - K_4$$

The variable CST setpoint provided a degree of flexibility in the control strategy; however, the constants K_3 and K_4 required adjustment durina control runs due to changes in sludge properties not totally reflected in solids content.

Additional control runs were conducted subsequent to the development of the CST2 model. Figure 24 presents typical on-line control data using the CST2 model for CST prediction and the CST setpoint calculated from the equation given above. In Figure 24a the predicted CST closely follows the CST setpoint value except for one 15-minute departure. The predicted CST and CST setpoint were recalculated approximately once every four minutes. The data presented in Figure 24b show significant deviations between the setpoint pH generated from the CST control loop and the measured feedback pH. The pH control loop, operating approximately once each minute, remained below the setpoint value over a 70-minute time span. In this case the minimum ferric chloride pumping rate was in excess of that required to decrease the pH to the calculated setpoint.

Problems with the CST control scheme were related to the fouling of the pH electrodes and changes in the sludge characteristics which were not reflected in the CST model or in the selection of the setpoint. Although short-term control was achievable using the CST model a suitable method for determining a setpoint for all sludges was not developed. Eventually, dose limits of 7% to 13% $FeCl_3$ (sludge solids basis) were implemented to eliminate severe excursions from the required dose. This control routine ignores calculated adjustments in pump speed which would cause the dose to fall outside the limits.

d. Dose Control

A ferric chloride dose ratio control was introduced as an alternate control strategy during the final months of the evaluation. The dose ratio strategy is defined by the following relationship:

[13] $$\text{Ferric chloride mass flow} = K_5\ (\text{sludge mass flow}) + K_6\ (\text{SSR-4})$$

The control strategy is based on a selected ferric chloride dose (K_5) and provides a degree of flexibility in order to reflect changing sludge characteristics (K_6). The advantages of the dose ratio strategy are: (1) maintenance problems with a feedback instrument are eliminated and (2) a given ferric chloride dose can be maintained which was not possible with the other strategies. Disadvantages are (1) there is no feedback instrument to allow corrective control adjustments, (2) the strategy relies on the accuracy of the sludge solids analyzer, and (3) a steady ferric chloride concentration in the day tank is required for proper dose control.

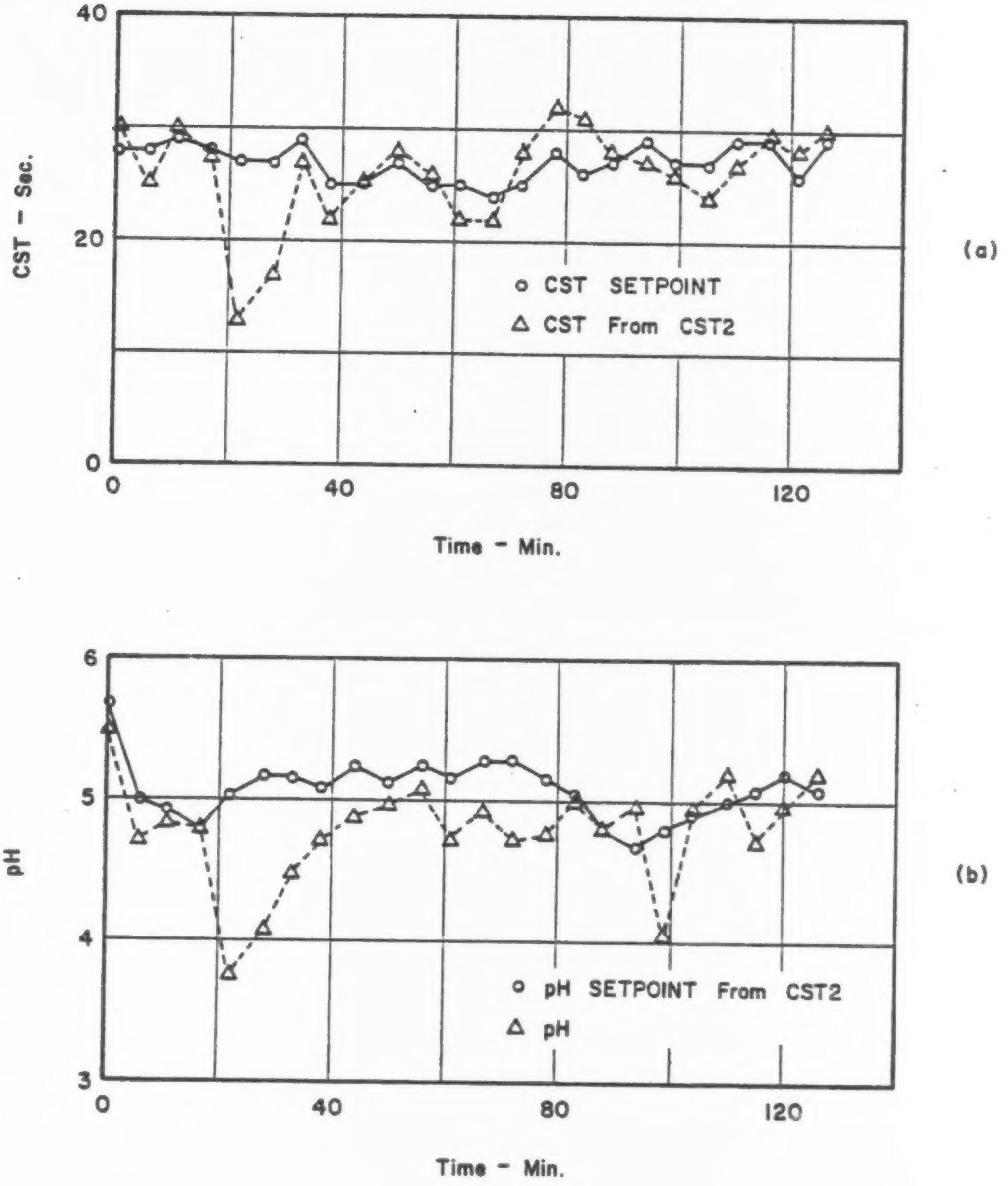


Figure 24. CST control using the CST 2 model.

The dose ratio control strategy was implemented during the June 24, 1981 filter and incinerator control run with the $K_5 = 0.11$ and $K_6 = 0$. A plot of ferric chloride dose fluctuations during the run is presented in Figure 25. During 15 hours of controlled operation a setpoint change was initiated on only one occasion and a consistent ferric chloride dose was maintained during the run. A wide variability in dose was observed in previous control runs in which pH or CST control strategies were employed. Manual intervention was substantially reduced from previous runs where frequent changes in setpoint pH or CST were required to control ferric chloride addition.

2. Lime Feed

A number of control schemes for lime addition were considered during the course of the project varying in complexity from a constant dose based on sludge solids to the SR models; however, shortly after the pH monitors were installed, it was observed that the filter yield dropped off dramatically when the pH of the lime conditioned sludge decreased much below 12.0. Under such conditions the cake moisture increased and the cake thickness decreased to a point at which cake would no longer discharge from the filter media. For this reason the only control strategy used for test runs was to setpoint the final pH to 12.0 or above. Although this strategy did not address the initial intent of controlling the specific resistance of the conditioned sludge it had two major advantages--it was relatively simple and it worked quite well.

Figure 26 presents typical on-line data collected during the June 24, 1981 test. The pH values represent readings recorded off the computer trend every four minutes and therefore indicate the general variation in pH around the setpoint (12.0). Although significant deviations from the setpoint pH are observed between 1400 hr and 1700 hr, no filtering problems were encountered due to the rapid response tuning required for the control of lime addition. Such deviations in the measured pH from setpoint are usually caused by significant changes in the other control loops which may subsequently affect the instantaneous pH reading such as changes in the raw suspended solids, sludge flow, or ferric chloride dose.

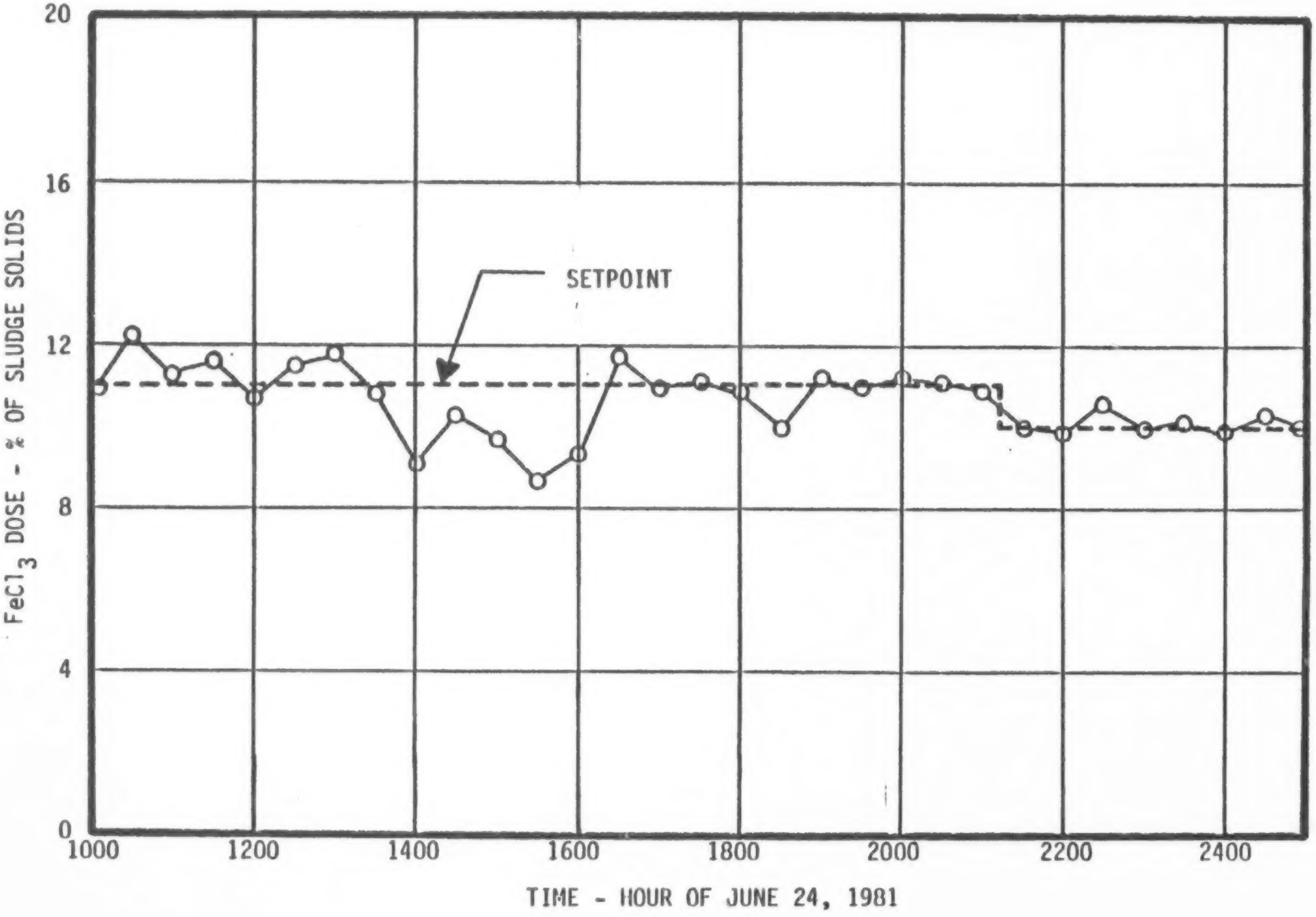


Figure 25. Ferric chloride dose control based on constant dosage.

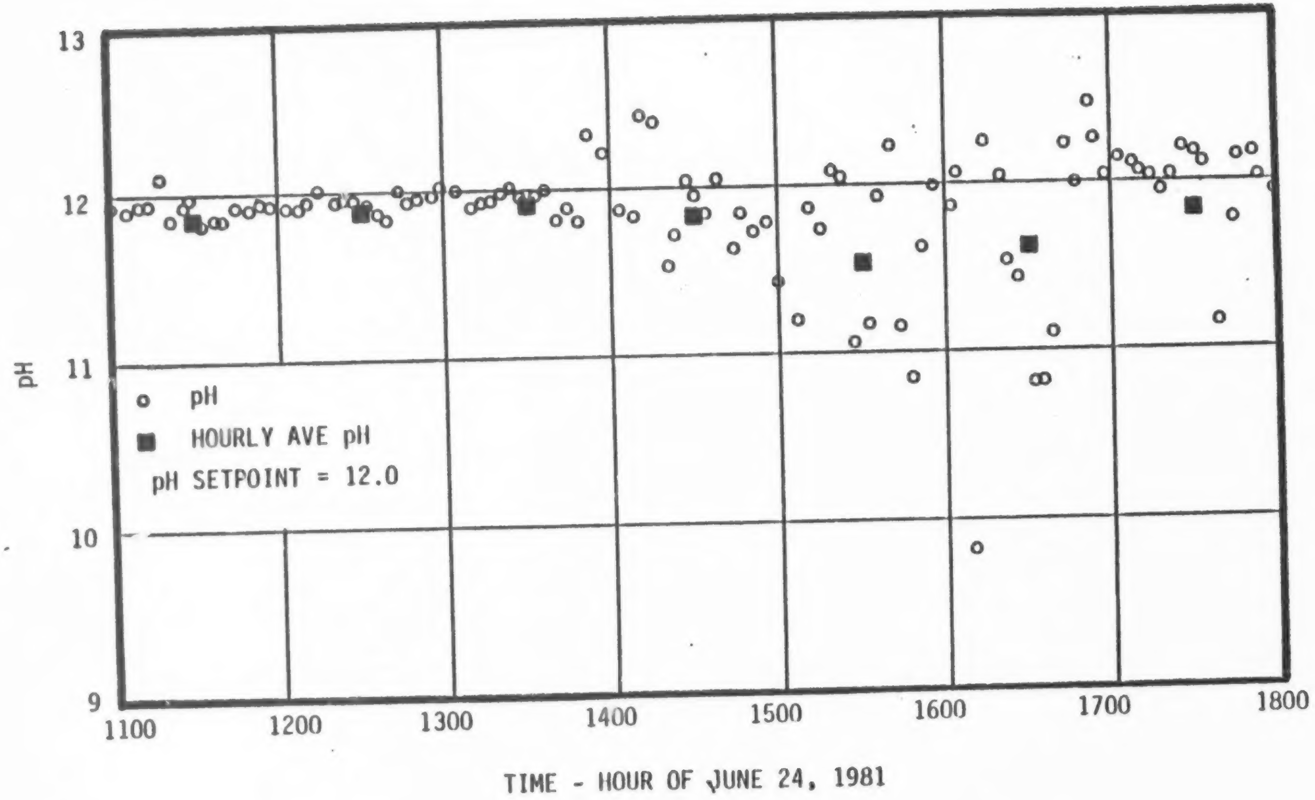


Figure 26. pH control for control of lime addition.

SECTION 11

VACUUM FILTER CONTROL

A. PRELIMINARY STUDIES

1. General

Preliminary observations of vacuum filter operation were conducted to identify control parameters influencing cake production. Typical manual operation usually resulted in a highly variable cake production which often caused difficulties in the control of the incineration process. Much of the variability in cake production was caused by changes in sludge characteristics or by inadequate control of chemical additions, due to mechanical problems or chemical overdosing. The goal of manual operation usually focused on the volume of sludge processed rather than the overall stability of the vacuum filter and incineration processes.

Initial attempts to develop filter control strategies were designed to reduce the variation in cake yield as well as maximize the production rate by stabilizing and controlling filter operating parameters.

2. Vat Conditions

a. Vat Level

Preliminary analyses of the effects of vat level adjustments on filter operation were based on observations during manual control. It was observed that when the vat level was lowered, at or near the lower control limit (approximately 15 cm (6 inches) above the base of the drum), loss of vacuum occurred more frequently causing filter upsets. When the level was raised to positions exceeding 64 cm (25 inches) from the base of the drum little improvement in dry yield was noted although the cake usually had a higher moisture content. It became apparent that although the operation of the filter at low vat levels and higher drum speeds required increased operator attention the cake quality improved because of the lower moisture content; however, in order to reduce the frequency of upsets and promote efficient cake release, most operators maintained the vat at relatively high levels.

Under manual control the vat level varies in response to all variables that affect a change in the filtration rate. For any reasonable combination of parameters the vat level reaches an equilibrium value between the lower limit and the vat overflow. Any change in dewatering characteristic, sludge flow, drum speed, or vacuum destroys the equilibrium and the vat level falls or rises to a new equilibrium position. It was observed that unless the chemical feed rates were excessive, the dewatering characteristics changed regularly and it was not possible for the operator to maintain the vat level at or near any given setpoint.

Open loop tests were conducted to determine the effect of vat level adjustments on cake quality and quantity. During the tests a closed loop controller was active to maintain the basin level at operator entered setpoints; however, the chemical feed pumps were controlled manually and no attempt was made to monitor dewatering characteristics. It is thus possible that changes in the dewatering characteristics may have impacted the observations. During the tests it was assumed that an interval of 45 minutes was sufficient for the effects of a change in the manipulated variable to pass through the process.

The results of the test conducted September 9, 1978 are summarized in Table 6. The increase in vat level did not appear to have a great impact on the wet cake production; however, the solids content decreased causing a substantial decrease in the dry cake yield. Although the data are difficult to interpret because of the uncertainty of the degree of conditioning, it was judged that vat level control was necessary if the goal of consistent cake quality and quantity was ever to be attained.

TABLE 6. VAT LEVEL OPEN LOOP TESTS

Vat Level	Dry Cake Production		Solids
inches	mt/hr	(ton/hr)	%
23	1.68	(1.85)	26.6
26.6	1.65	(1.82)	26
30.2	1.59	(1.75)	24.9
33.8	1.59	(1.75)	24.2
26.6	1.45	(1.6)	25.5
19.4	1.5	(1.65)	26.4

The general schematic for the vat level control is presented in Figure 27. The speed of the raw sludge pump is controlled to maintain the vat level at the setpoint value. The algorithm is a cascade control loop. The internal loop consists of a flow controller which receives the sludge flow rate signal as feedback and outputs a speed adjustment signal to the pump motor. The outside cascade loop provides the flow setpoint to the flow controller. The digital filter is required to dampen the output of the local monitor and eliminate the effect of waves generated by the agitator.

It was originally envisioned that the level control algorithm would utilize a number of inputs, including cake moisture, to calculate the desired setpoint. When this option is not used the operator may enter a setpoint value.

The vat level control system using an operator entered setpoint was the first control loop put into service. This was done because the control was

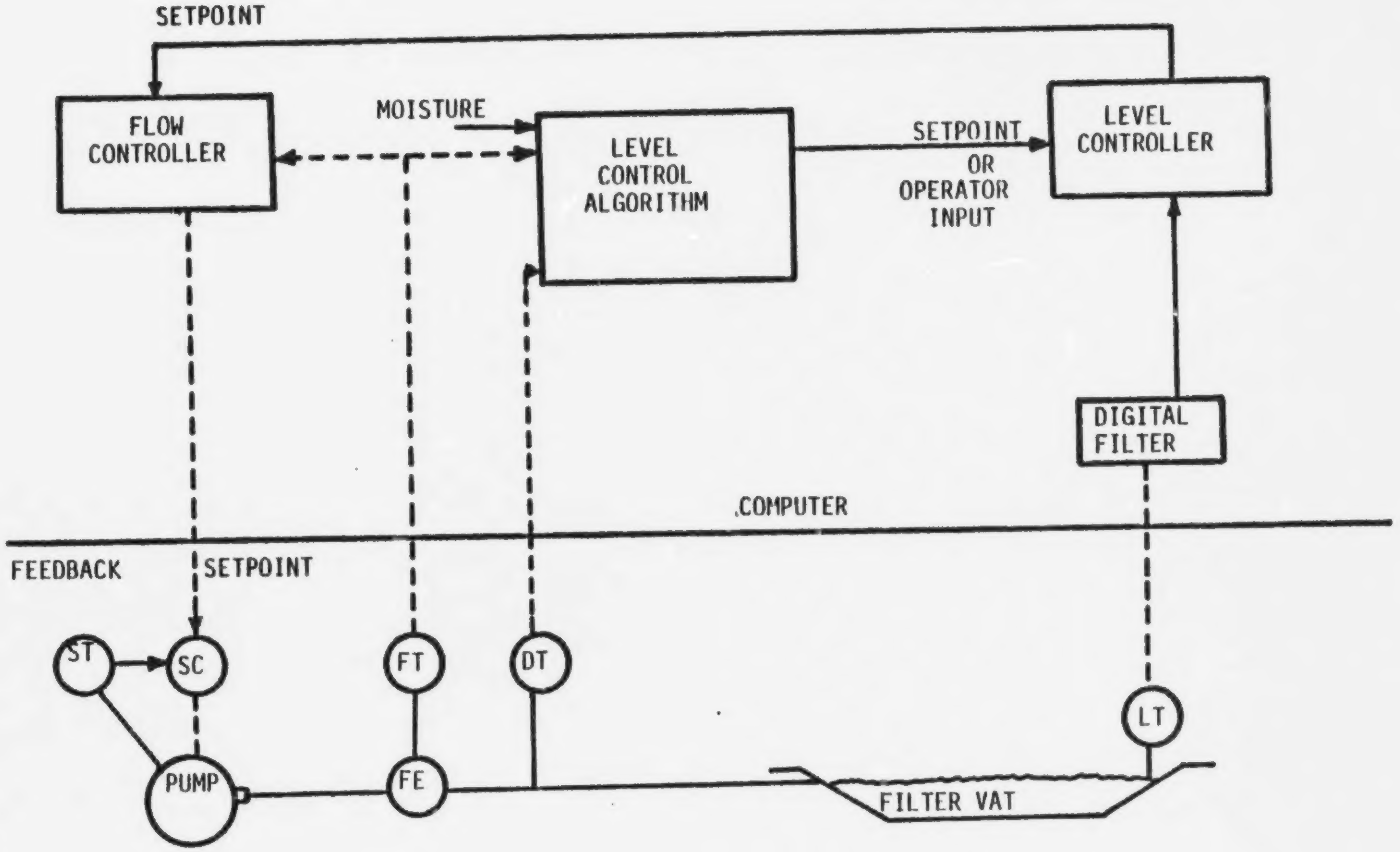


Figure 27. Filter vat level control schematic.

relatively simple and vat level control was required to conduct all open loop tests including those dealing with vat level.

b. Agitator Speed

During studies of manual filter operation it was observed that operators would sometimes use very high agitator speeds to thin the filter cake during periods of excess cake production. In order to verify these preliminary observations tests were conducted to study the relationship of agitator speed to filter cake production, cake moisture content, and raw sludge input. The tests were conducted at several vat levels; and, the vat level and chemical conditioning control loops were in computer mode. The filter drum was maintained at a constant speed during each test. Changes in agitator speed were conducted manually.

Typical results of the tests are presented in Figure 28. The wet cake production rate, along with the raw solids flux, decreased dramatically when the agitator speed was increased beyond 10 cycles/min. In addition the cake moisture also increased at the higher agitator speeds. Based on these observations the decision was made to continue manual control of the agitator, and to maintain the speed at approximately 10 cycles/min.

3. Drum Speed

The initial observation of manual control demonstrated the existence of definite relationships between drum speed, cake quality, and the probability of filter upsets. At lower drum speeds the cake had a lower solids content, was thicker, and discharged from the media readily. As the speed was increased the cake became thinner and dryer. Increased operator attention was required at the higher speeds to assure continuous cake discharge. Excessive drum speeds resulted in a sharp drop in cake production because of poor cake release.

The results of an open loop test conducted September 1, 1978 are summarized in TABLE 7. The test was conducted over a 3.5 hour period during which time the vat level was maintained constant. Cake production increased dramatically as the drum speed increased and the solids content of the cake decreased; however, the dry cake production, or yield, increased as the yield equation predicts it should. Based on these simple observations it was obvious that the ability to adjust the drum speed in a controlled manner would provide a method of controlling both the cake production rate and moisture content. It should be pointed out that the drum speeds used in this test were extremely high and were possible only because of thick, well conditioned sludge and a high vat level.

The drum speed control schematic is presented in Figure 29. The speed control loop consists of a controller receiving feedback from the drum tachometer and outputting adjustment signals to the drum drive motor. The speed setpoint can be entered by the operator or can be calculated using a yield model which utilizes a number of inputs.

4. Cake Yield

Gale and Baskerville (7) demonstrated that the yield equation, Eq [1], does

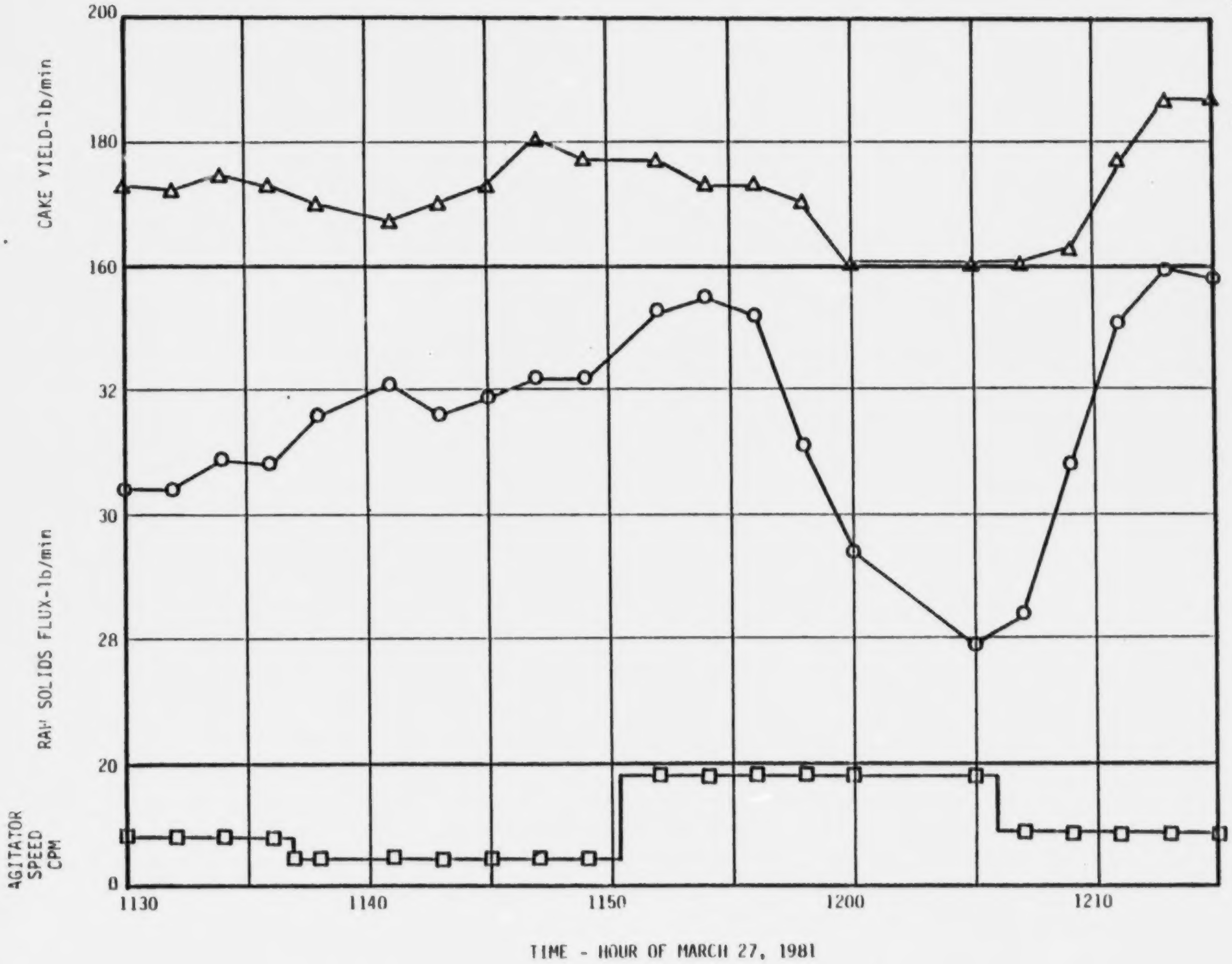


Figure 28. Relationship between agitator speed, raw solids flux, and wet cake yield.

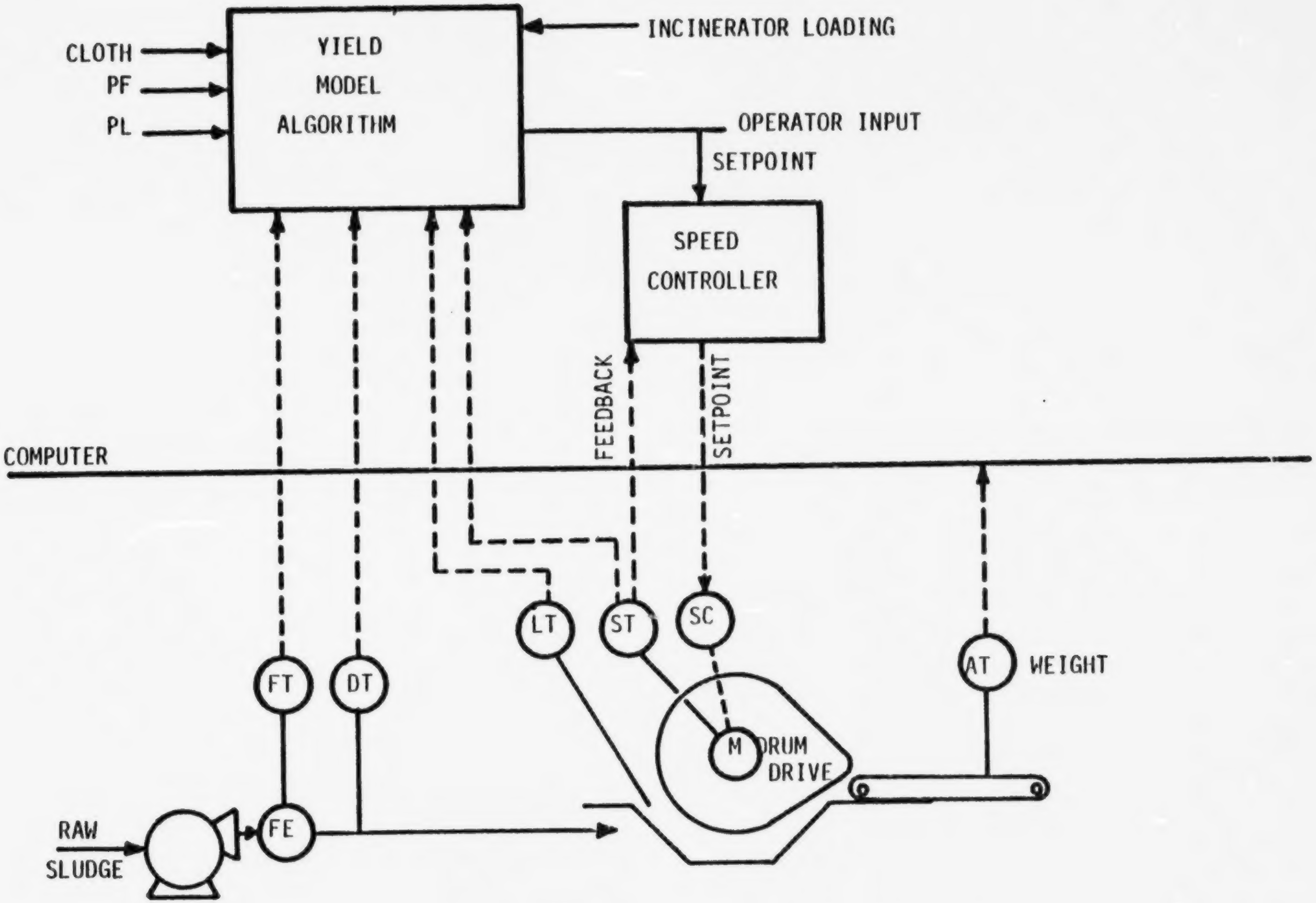


Figure 29. Vacuum filter control schematic.

in fact predict the yield of a vacuum filter reasonably well. During the period of November-December, 1978, a total of 18 data sets were collected to characterize sludge dewatering characteristics--see Section 9.A.2. Several weeks later the filter parameters (submergence, rotational speed, vacuum, and cake production) were extracted from the computer log and operator's log for the time periods corresponding to the sampling of the conditioned sludge. Filter yields were calculated using Eq [1] and also from the observed cake moisture content and wet production rate.

TABLE 7. DRUM SPEED OPEN LOOP TESTS

Drum Speed rev/hr	Dry Cake Production mt/hr	Dry Cake Production (ton/hr)	Solids %
15	1.32	(1.45)	28.2
20	2.10	(2.31)	28
25	2.27	(2.50)	26
30	2.31	(2.55)	26.4
35	2.36	(2.60)	27.6

The observed and corresponding calculated yields are summarized in Figure 30. Although the values were not equal, a moderate correlation, R = 0.80, was observed. Unfortunately, the yield calculations were an after thought; and, as a result, the calibration status of the online instruments used for monitoring vat level, vacuum, and cake production was not known. On several days the computer was not operating and the operator's log was used as a source of information; however, the time of the entries did not always correspond to the sampling time. One additional reason for the discrepancies between the calculated and observed yields relates to the status of the filtration media. The specific resistance was determined with a clean medium each time. Based on operating experience the filter yield is reduced significantly as the medium becomes fouled.

B. ON-LINE DATA

1. Collection Procedures

A variety of instrumentation was installed on the vacuum filter in order to gather on-line data which could be used to monitor and control the operation of the filter. The instrumentation included a drum speed tachometer and remote drive unit, agitator speed tachometer, vat level monitor, filtrate turbidity, form and dry vacuum transmitters, and a cake thickness indicator. Existing instrumentation was used to monitor the sludge feed and cake production rates.

All on-line data generated from the vacuum filter instrumentation were printed out as hourly averages on the computer trend report. The hourly average data represented computer scans operating on an 8-second cycle. Instrumentation outputs and calculated operating parameters selected for more

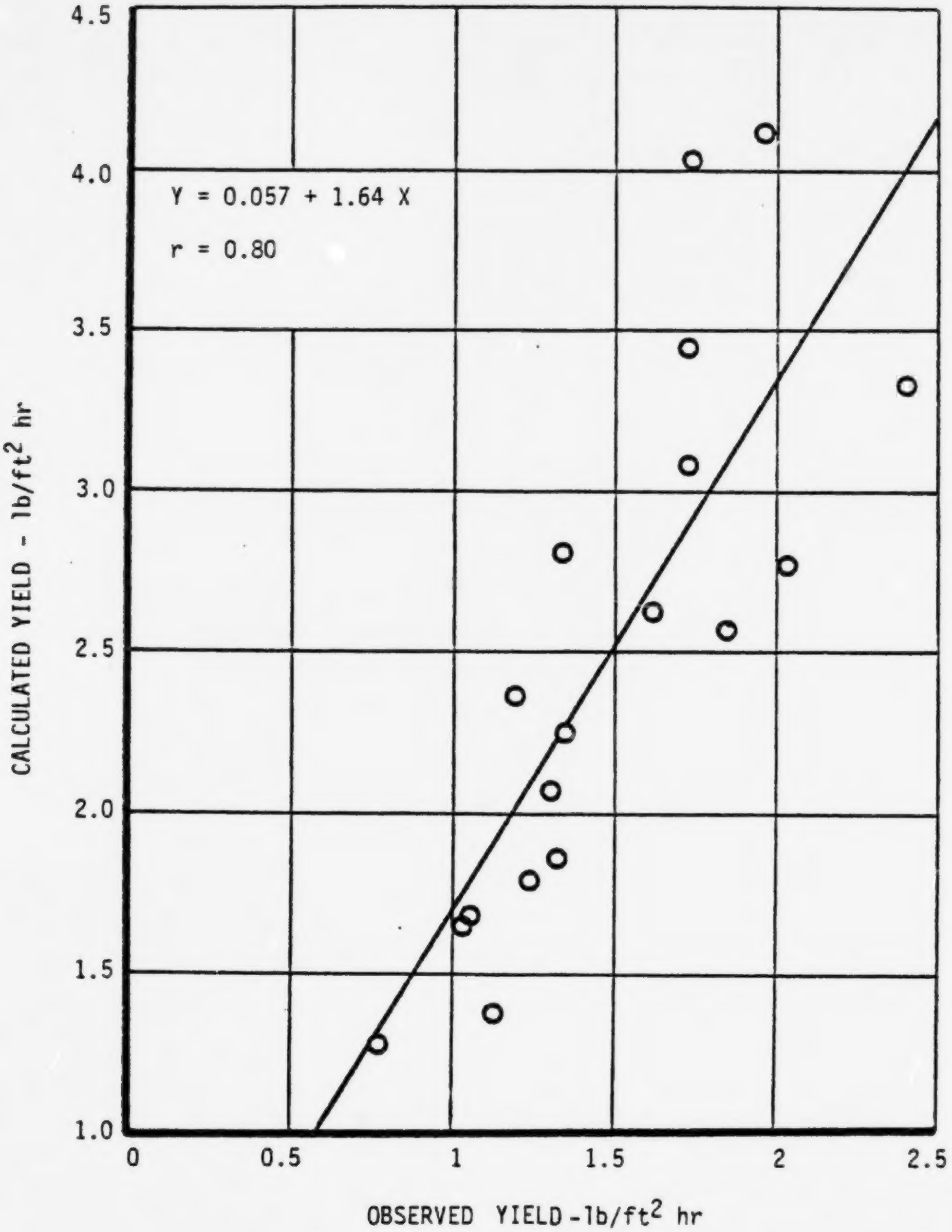


Figure 30. Relationship between observed and calculated filter yield.

frequent observation were printed out at desired frequencies ranging from 30 seconds to 10 minutes. Filter cake grab samples for moisture analysis and sludge samples for specific resistance tests were correlated to both sludge and filter parameters recorded on the trend report at the time of sampling. Operating reports were printed every 8 hours for both the manually operated and controlled filters for longer term comparisons. Inspection and calibration procedures were routinely conducted on all pertinent instrumentation to provide reliable comparison data.

2. Summary

Prior to 1980 short term vacuum filter studies employed on-line data taken from local meter readings and manual control settings. Continuous on-line data collection and report generation was initiated early in 1980 in order to provide input for modeling efforts involving filter cake moisture and cake yield. A total of 64 data sets were collected during March, July, and August, 1980. These data are summarized in TABLE 8 and represent an extension of the data set previously presented in TABLE 2 for lines 097 through 160. Several new parameters are introduced and they are defined in TABLE 9.

TABLE 9. FILTER OPERATING PARAMETERS

Symbol	Definition
VAC	Vacuum in form zone, inch Hg
VAT	Submergence of filter drum, inch
DRUM	Rotational speed of filter drum, revolution/hour
TPH	Wet cake production rate, ton/hour
SSF	Total solids concentration in cake, % solids
FLOW	Raw sludge flow, gpm
CLOTH	Operating hours since media acid cleaned, hour
SR3	Specific resistance of conditioned sludge calculated from the yield equation, m/kg

It was anticipated that the variable CLOTH would provide a measure of the resistance to filtration presented by the filter medium. Because a considerable amount of time was required to determined the specific resistance of the conditioned sludge using the Buchner tunnel technique, the decision was made to monitor the filter operating parameters and subsequently solve the yield equation, Eq [1], for specific resistance directly.

C. MODELING ATTEMPTS

1. Cake Moisture

After demonstration tests of on-line moisture analyzers indicated that there were no reliable instruments available, development of optimization control strategies based on cake moisture was discontinued; however, the need for

TABLE 8. SUMMARY OF ON-LINE FILTER DATA

LINE	DATE 1980	Q	SSR	PF	PL	SRL	SR3	TPH	TS	VAC	VAT	RPH	CLOTH
097	303	106	3.5	8.2	40	1.20	2.21	5.60	22.6	22.0	21.4	19.0	62
098	303	105	3.5	8.2	40	1.25	1.67	6.20	23.7	22.0	21.7	18.8	63
099	311	87	5.8	6.9	18	1.60	1.22	6.30	21.8	22.0	18.5	13.4	132
100	311	85	5.0	7.2	23	1.95	2.24	5.30	21.4	22.0	17.2	13.4	133
101	311	85	5.2	8.0	22	1.90	2.15	5.80	20.7	22.0	17.8	13.4	133
102	311	85	5.1	7.9	22	2.15	2.22	5.60	20.9	22.0	18.6	13.4	134
103	311	85	4.7	8.7	27	2.50	2.73	5.10	20.3	22.0	19.8	13.4	134
104	311	84	5.0	8.3	26	2.40	2.90	5.30	19.7	22.0	20.3	13.5	135
105	311	85	4.9	8.7	25	2.45	3.43	4.80	19.7	22.0	22.1	13.5	135
106	311	84	5.0	8.4	25	2.60	3.95	5.00	18.8	22.0	23.5	14.6	135
107	311	83	5.0	9.2	20	2.05	2.34	5.40	20.7	22.0	14.5	14.4	136
108	314	104	4.4	7.3	19	2.80	3.04	5.30	21.1	22.0	18.8	20.8	40
109	314	103	4.3	7.5	20	2.70	3.02	5.50	20.1	22.0	18.6	20.3	40
110	314	103	4.3	7.5	20	2.60	3.38	5.20	20.9	22.0	17.3	22.8	41
111	314	103	4.2	7.6	20	2.70	3.32	5.20	20.8	22.0	17.0	22.8	41
112	317	100	5.9	5.7	14	1.45	1.42	6.50	22.6	21.0	13.1	15.3	107
113	318	100	5.2	5.7	19	2.00	1.25	7.10	20.7	23.0	25.4	10.3	14
114	318	98	5.2	5.5	19	2.10	1.49	6.10	21.6	23.0	27.2	10.1	16
115	318	97	5.3	5.5	19	2.25	1.25	6.80	21.8	23.0	27.4	10.1	16
116	318	96	5.5	5.3	18	1.85	1.31	6.70	21.8	23.0	26.9	10.1	16
117	318	95	4.4	6.9	24	1.70	1.11	7.00	22.8	23.0	25.5	11.9	17
118	318	89	4.7	6.9	24	1.65	0.97	7.00	25.0	23.0	14.9	13.7	17
119	318	90	4.8	6.6	23	1.40	1.26	5.50	25.9	23.0	11.1	13.8	18
120	318	87	5.0	6.0	21	1.55	1.16	5.90	25.8	23.0	11.6	13.7	18
121	320	99	4.5	8.6	33	1.85	2.44	4.50	23.3	22.0	19.5	13.4	59
122	320	99	4.3	7.5	37	1.70	2.34	4.70	23.0	22.0	20.1	13.6	60
123	320	97	4.2	7.9	36	2.05	2.23	4.60	23.5	22.0	20.2	13.4	60
124	321	100	5.1	5.7	16	2.45	1.72	5.40	22.0	22.0	18.4	12.3	87
125	321	99	4.7	6.2	18	2.40	1.62	5.60	21.2	22.0	19.3	12.1	88
126	321	99	4.4	6.6	16	2.45	1.34	5.60	22.2	22.0	18.8	12.1	88
127	321	99	4.3	6.9	14	2.45	1.59	5.20	21.5	22.0	19.4	12.2	89
128	724	100	3.4	15.7	24	2.10	1.95	3.93	14.7	5.2	24.4	16.9	51
129	724	95	3.4	9.3	14	2.75	1.96	2.95	16.2	5.5	19.7	13.5	52
130	724	111	3.3	15.0	22	1.95	0.90	5.20	15.2	5.1	22.6	15.8	52
131	724	149	3.4	9.3	11	2.90	2.50	5.06	19.8	19.7	26.2	15.9	53
132	724	103	3.2	19.6	34	2.15	1.23	4.99	18.1	8.5	30.9	14.5	54
133	724	115	3.3	15.6	18	1.75	0.81	6.11	18.1	12.3	33.8	10.0	55
134	724	107	3.6	8.0	14	2.35	2.13	4.66	22.1	20.1	23.7	16.0	56
135	724	139	3.6	15.0	19	1.45	1.02	6.78	18.1	12.5	23.0	16.0	56

TABLE 8. CONTINUED

LINE	DATE 1980	Q	SSR	PF	PL	SRL	SR3	TPH	TS	VAC	VAT	RPH	CLOTH
136	724	105	3.5	14.1	22	1.55	0.84	5.03	19.8	9.5	14.3	13.5	57
137	729	111	3.3	12.2	21	1.80	0.31	8.17	15.9	6.0	24.1	11.0	24
138	724	105	3.6	13.1	20	1.50	1.01	5.75	17.9	9.0	21.6	13.5	58
139	729	123	3.2	11.8	14	2.40	0.63	7.33	17.0	9.6	23.0	14.9	25
140	729	128	3.2	9.3	18	3.15	1.05	6.48	20.0	16.6	28.4	14.9	25
141	729	117	3.5	10.6	21	1.45	0.66	6.71	22.3	16.9	16.9	12.5	28
142	729	120	3.3	13.5	13	2.20	1.01	7.08	20.4	18.8	29.1	14.9	27
143	729	102	3.5	14.7	17	1.50	0.43	7.67	17.0	9.0	19.8	10.4	29
144	729	105	3.6	13.5	15	2.55	0.99	5.70	22.3	18.5	17.9	12.5	27
145	729	135	3.2	12.5	19	2.10	0.47	8.97	15.7	7.7	28.0	14.9	26
146	729	116	2.9	12.1	13	2.75	0.93	6.17	20.6	16.3	22.6	15.2	29
147	729	124	3.1	11.0	18	2.10	0.52	8.46	17.3	10.2	22.6	15.2	30
148	807	91	4.4	11.0	19	1.40	0.95	6.50	23.2	17.0	16.2	15.2	14
149	807	109	4.5	13.0	15	1.10	0.77	8.20	19.7	14.0	17.4	15.1	15
150	807	136	4.2	8.0	16	1.40	1.04	8.30	18.1	17.5	23.5	15.1	15
151	807	94	4.5	8.0	18	1.55	1.09	5.80	22.9	16.5	13.6	15.1	16
152	808	91	4.5	7.0	10	3.45	2.04	5.20	22.1	20.0	24.4	15.1	36
153	808	112	4.5	9.0	14	1.35	0.96	6.90	20.4	14.0	22.6	15.1	36
154	808	113	4.5	11.0	17	1.15	0.87	7.40	18.2	11.0	23.3	15.1	37
155	808	85	4.7	14.0	20	1.05	0.81	6.80	17.4	8.0	15.0	15.1	37
156	808	72	4.6	12.0	13	1.50	1.04	5.30	19.8	10.0	15.1	15.1	38
157	808	63	4.7	12.0	31	1.30	0.66	6.30	21.0	7.5	15.9	15.1	38
158	808	76	4.6	8.0	12	3.10	1.64	4.20	24.4	17.0	11.0	15.1	39
159	808	71	4.6	13.0	27	1.20	0.79	6.20	18.2	7.5	10.5	15.1	39
160	808	82	4.7	16.0	20	1.10	0.58	7.00	18.6	7.0	10.4	15.1	40

measuring or calculating moisture to determine relative cake quality was evident. Two attempts were made to develop a method of continuously modeling cake moisture. One employed a solids balance calculation involving dry solids mass flow and wet cake production. The second method employed a stepwise regression analysis of measurable on-line parameters.

The cake solids content was calculated by adding the sludge dry solids and dry chemicals then dividing by the wet cake tonnage. Although this method could provide an hourly average value, it was not practical as a continuous measure of solids content due to variable time lags and storage changes caused by vat level fluctuations. In addition the cumulative errors in determining cake tonnage, sludge solids, flow rates and chemical concentrations made frequent calibration of all parameters necessary. Although the hourly and 8-hour shift reports recorded the hourly average calculated cake solids with general accuracy, the calculated value was sometimes well out of the range of normal cake solids content.

The second modeling effort was an attempt to relate cake solids, SSF, to the characteristics of the sludge, TABLE 1, and the filter operating parameters, TABLE 9. Multiple regression techniques were again used. The results of the analyses indicated that filter operating parameters were much more important than the sludge characteristics. The resulting expression of SOLID defined as the predicted cake solids expressed in %, is as follows:

[14] $\text{SOLID} = 18.0 + 0.39\ \text{VAC} - 0.19\ \text{VAT} - 0.03\ \text{CLOTH} + 0.06\ \text{PL}$

Coefficient of multiple regression = R = 0.9

This model provided a higher correlation to cake solids than any of the moisture analyzers previously evaluated; however, subsequent comparisons of predicted cake solids and measured values yielded errors of up to 2% solids which was considered unacceptable for process control.

2. Cake Yield

Preliminary evaluations, Section 10.A.4., indicated that the performance of the vacuum filter itself might be used to estimate the specific resistance of the conditioned sludge and thus provide the necessary feedback for a conditioning control scheme. The yeild specific resistance, SR3, was determined for each of the 64 data sets presented in TABLE 8. Multiple linear regression techniques were then used to develop a relationship between SR3 and the measured sludge characteristics and the filter parameter CLOTH.

From the regression matrix, presented in TABLE 10, it is obvious that the variable CLOTH had the major impact in determining the values of SR3. This observation was not unexpected. The stepwise regression technique demonstrated that consideration of variables in addition to CLOTH, PF, and PL, did not significantly improve the goodness of fit for a predictive model of SR3. Although a number of squared terms and cross products were tried, the best model for predicting SR3 was as follows:

[15] $\text{Predicted SR3} = 1.55 + 0.015\ \text{CLOTH} - 0.112\ \text{PF} + 0.031\ \text{PL}$

Coefficient of multiple regression = R = 0.71

Since only approximately 50% of the variability in SR3 is explained by the combined influence of the independent variables ($R^2 = 0.50$) the model accuracy is not sufficient for process control. The relatively poor fit was due, in part, to the fact that the cake was assumed to be noncompressible; whereas, it was demonstrated this was not the case at Seneca. Subsequent evaluation of this model demonstrated that the predicted value of SR3 using Eq [15] may deviate substantially from the observed value. Although this modeling effort was not successful it did demonstrate the importance of maintaining the filter cloth in a clean condition.

TABLE 10. REGRESSION MATRIX FOR SR3

	SR3	CLOTH	SSR	PF	PHL	PHF	PHD	ORPD
CLOTH	0.62	-	-	-	-	-	-	
SSR	0.33	0.37	-	-	-	-	-	-
PF	-0.42	-0.19	-0.62	-	-	-	-	-
PHL	0.10	0.09	-0.04	-0.20	-	-	-	-
PHF	0.09	0.45	0.01	0.09	-0.10	-	-	-
PHD	-0.02	-0.30	0.00	-0.11	0.10	-0.96	-	-
ORPD	0.02	-0.29	0.29	-0.42	0.06	-0.84	0.82	-
PL	0.28	0.20	0.00	0.03	0.47	-0.23	0.25	0.14

D. CONTROL STRATEGY DEVELOPMENT

1. General

The overall objective of the vacuum filter control system was to maintain a constant cake production rate with only slight variation in the cake moisture and volatile content and, at the same time, maximize filter yield in terms of sludge solids. Since all attempts to estimate cake moisture by direct and indirect methods were unsuccessful, the operating goal for filter no. 1 reverted to the maintenance of a constant cake production rate and, at the same time, maximizing the raw sludge pumping rate. It was anticipated that control of the chemical feed systems would provide a reasonably conditioned sludge and that large excursions in cake moisture and volatile content could be avoided.

As a practical matter only two variables are available to the operator, or computer, to adjust cake production rate, the vat level, which determines the fraction of the cycle time in the form zone, and the filter cycle time. The vacuum in the form zone, which also appears as a variable in the yield equation, is usually maintained at the highest value possible.

Because of problems with the vacuum system, the vacuum varied considerably during the course of the study; however, the cake production rate was not impacted significantly. At first this appeared to contradict the effect predicted by Eq [1]; however, this relationship is valid only for noncompressible cakes. For the general case the yield is expressed as follows:

$$[1a] \qquad L = \left[\frac{2P(1-Swk)}{\mu R_g \; Tc}\right]^{\frac{1}{2}}$$

Where: S = Coefficient of compressibility--see Vesilind (6) for method. A subsequent test demonstrated that the specific resistance of the conditioned sludge was a function of the test vacuum. For that one test the coefficient of compressibility was found to be approximately 0.96. Although the value of S may vary substantially, the one value obtained supports the observation of no relationship between L and P. Because of the laboratory time involved, cake compressibility was not addressed in any further detail; and, the vacuum was generally maintained at the highest value possible.

Automated control of the vat level and drum speed was initiated early in the project using the loops illustrated in Figures 27 and 29. The actual control algorithms were developed on a semi empirical basis during the subsequent 1.5 year period. In order for a particular strategy to be successful it had to maintain filter operation without manual intervention while responding to the variability of the incoming sludge.

2. Vat Level

The vat level control scheme illustrated in Figure 27 was initially instituted using operator entered setpoint values. The data presented in Figure 31 demonstrate that the level control loop functioned satisfactorily; however, the results of initial tests demonstrated that a steady state level did not assure a steady production rate even when drum speed and vacuum were held constant.

The variable production rate was no doubt related to the variable nature of the conditioned sludge. Since the capability existed to vary the vat level setpoint the decision was made to define the setpoint as a function of a cake thickness. Cake thickness is a relatively important operating parameter for a vacuum filter. Thin cakes may not discharge from the cloth and thick cakes have a higher moisture content. Because attempts at thickness measurement were not successful the cake thickness was calculated from the production rate, drum speed, and the cloth area. The setpoint was defined as follows:

$$[16] \text{ Vat level setpoint} = K_7 - K_8 \times (\text{thickness})$$
$$\text{expressed in terms of inch/100}$$

By judicious choice of the constants, K_7 and K_8, Eq [16] can be used to provide reasonable setpoint values for a wide range of sludge characteristics. If the calculated thickness decreases significantly the setpoint level increases. The increased vat level will yield a thicker cake and assure discharge from the cloth. If, on the other hand, the observed thickness increases, the setpoint decreases. The reduction in vat level yields a thinner cake with a lower moisture content. The control action also reduces the chance of filter upsets by increasing the level setpoint when lower cake production rates (thin cakes) are observed due to low sludge solids or filter media blinding. A constant setpoint can be implemented by setting K_8 to zero.

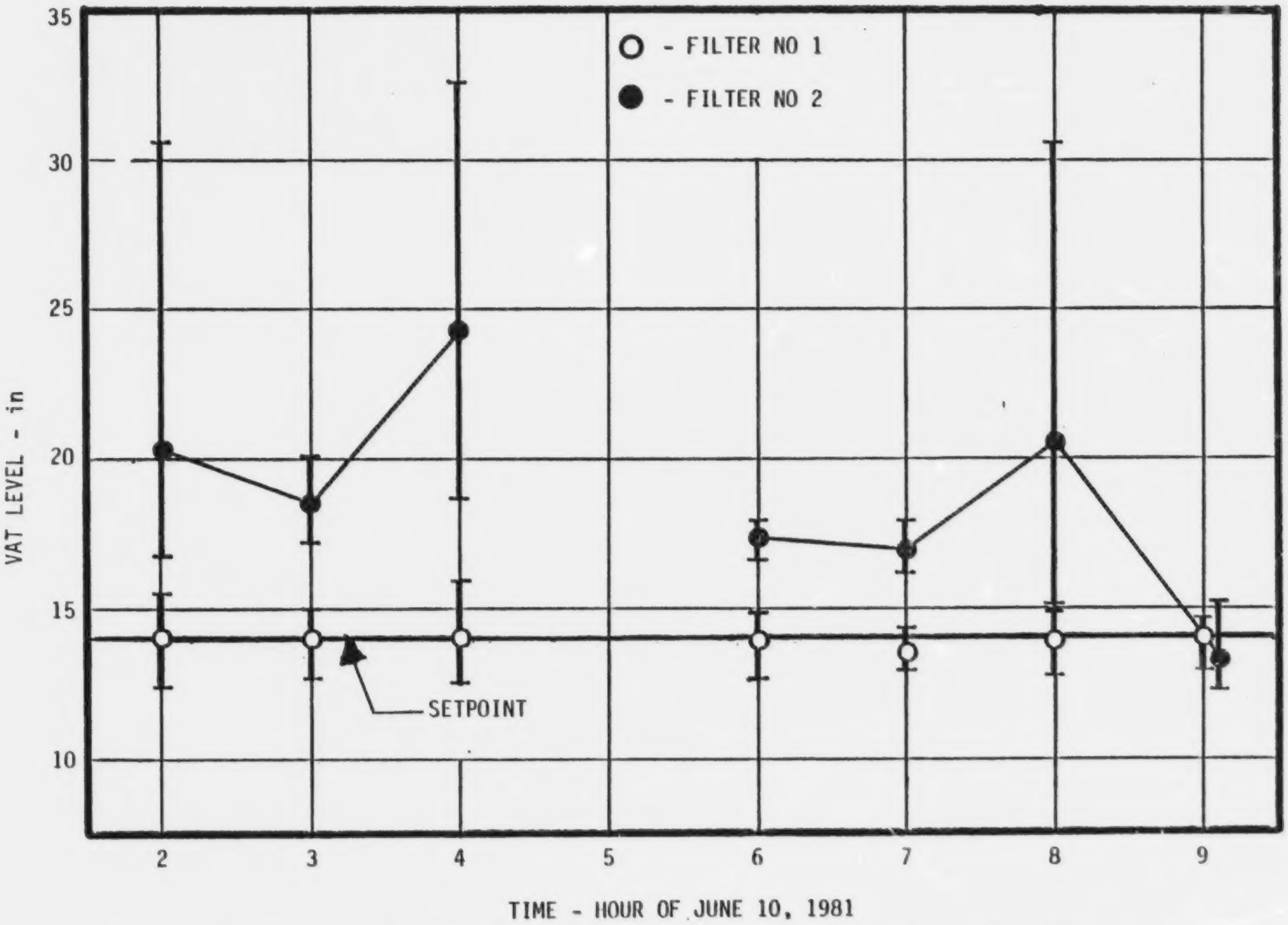


Figure 31. Hourly vat level variations for automated and manual control.

3. Drum Speed

The initial speed control strategy was based on a cake production setpoint. If the observed production rate deviated significantly from the setpoint value the drum speed setpoint was adjusted in proportion to the deviation. The setpoint adjustment was, however, limited to one RPH in any one step. This strategy increased or decreased the drumspeed setpoint as the cake production rate decreased or increased respectively; and, reasonable control was maintained if the raw sludge characteristics did not change significantly. If, however, the raw sludge solids content decreased significantly the speed setpoint would continue to increase gradually. This caused the cake thickness to decrease until the critical point was reached at which the cake no longer discharged. In summary, this strategy failed because it could not recognize that the goal was not attainable.

The second attempt at developing a successful strategy was based on a cake thickness setpoint. If the observed thickness deviated significantly from the setpoint the drum speed was adjusted in proportion to the deviation.The one RPH limitation was maintained. If the raw sludge solids did not change dramatically ($\leq 0.5\%$) the thickness control functioned; however, the cake production was not steady which caused problems with the incinerator operation. Considerable difficulty was encountered in determining the proper setpoint for a particular sludge. If the setpoint thickness could not be attained the drum speed would eventually reach its minimum or maximum speed or cause a failure related to cake discharge as above. This system was basically unstable because the drum speed setpoint was a function of the calculated cake thickness which in turn was a function of drum speed.

Subsequent attempts at drum speed control again utilized a cake production setpoint; however, the setpoint value was adjusted as a function of the raw sludge solids content as follows:

$$[17]\ \text{Cake Production Setpoint} = K_9 + K_{10}\ (\text{SSR})$$

A filter recovery mode was also added which decreased the drum speed to a fixed value (operator entered) whenever the cake production fell below a predetermined value. Eventually an upper limit was placed on the drum speed, approximately 18 RPH, to prevent filter failure due to cake discharge problems. The upper limit also facilitated the use of a constant cake production setpoint ($K_{10} = 0$) without encountering frequent upsets.

The results of a seven-hour test are summarized in Figure 32. Both the vat level and cake production setpoints were operator entered ($K_8 = K_{10} = 0$). The vat level setpoint was maintained at one value during the test; but, the production setpoint was adjusted twice, at 1130 hrs and 1520 hrs. The cake production data were obtained from the trend report at 4-minute intervals. The incremental increases in drum speed were in response to production rates below the setpoint value. The filter recovery mode was activated at approximately 1515 hrs when the production rate fell dramatically following an upset. The control system brought the filter back into production without manual intervention. The upper limit on drum speed was reduced approximately 1 RPH (17.8 to 16.9) at that time to prevent further upsets related to excessive speed.

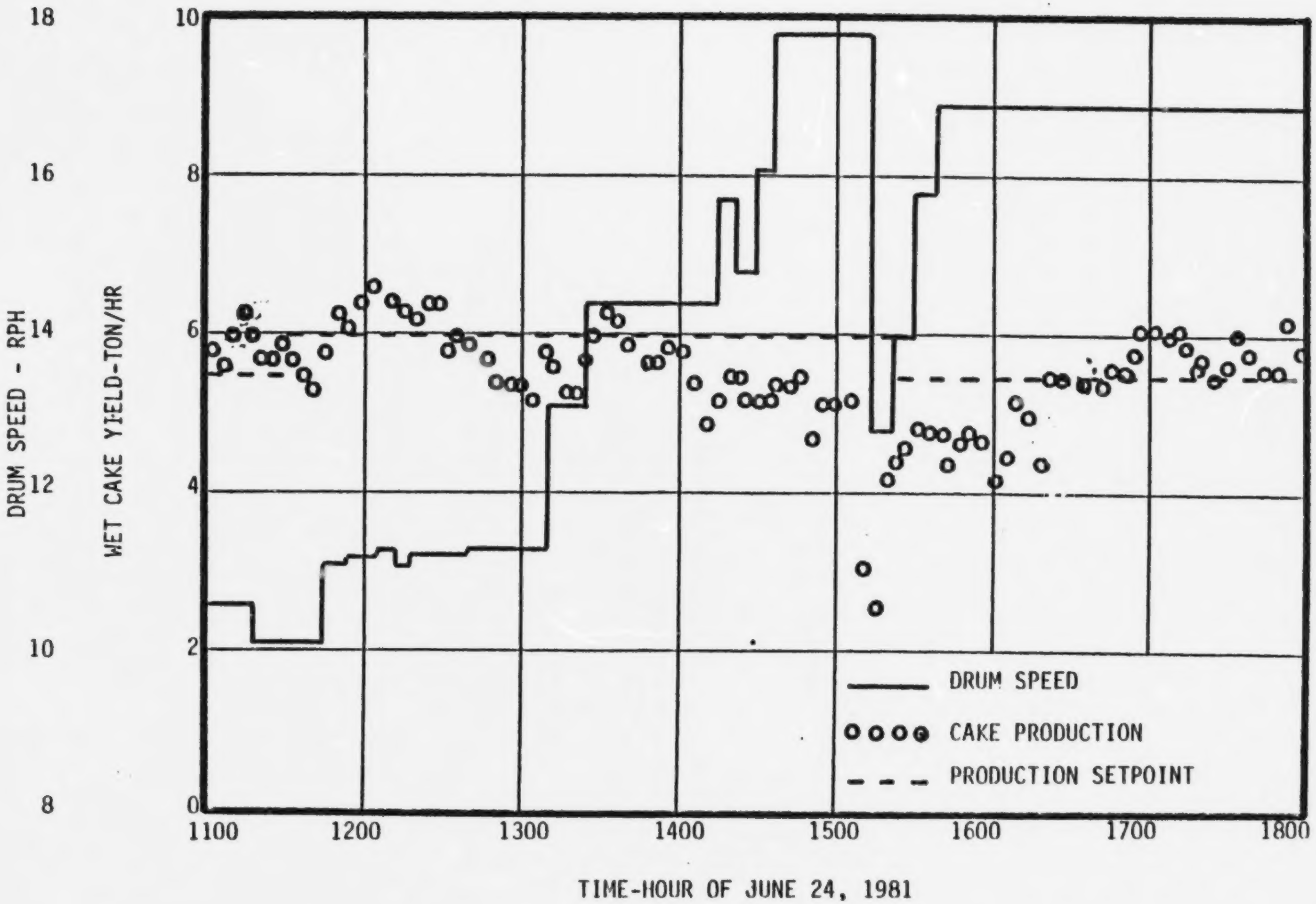


Figure 32. Variations in cake production during automated control.

EVALUATION OF AUTOMATED DEWATERING SYSTEM

A. GENERAL

The overall evaluation of the control system was based on a comparison of vacuum filters no. 1 (automated) and no. 2 (manual) in terms of filter performance and cost. Data were collected during a parallel demonstration test early in April, 1981. That test lasted approximately 63 hours; however, an additional 175 (approximately) complete data sets were collected during the 12-month period July, 1980 through June, 1981 as summarized in TABLE 11. In addition, manual operation was monitored on both filters for a total of 290 hours.

TABLE 11. SUMMARY OF OPERATING HOURS WITH COMPLETE DATA SETS

	Hours		
	Filter No. 1		
Month	Manual	Computer	Filter No. 2
July (1980)	-	15	-
August	-	12	-
September	38	55	59
October	19	30	3
November	10	8	9
December	18	7	2
January (1981)	-	-	-
February	2	2	1
March	4	6	4
April	3	55	57
May	-	-	-
June	11	44	50
TOTAL	105	234	185

Complete data sets, in terms of this evaluation, are defined in TABLE 12. The complete data sets collected are presented in Appendix B. In addition, partial data sets were collected consisting of a minimum of hourly averages for: raw sludge flow and solids, ferric chloride and lime dose, and wet cake production rate. The approximate number of partial sets collected for no. 1 manual, no. 1 computer, and no. 2 manual were 1140, 250, and 900 respectively.

The data collection schedule is summarized in TABLE 13. If one of the listed parameters was not monitored, the data for that hour were not used.

Throughout the project, scheduled and unscheduled maintenance on the sludge processing equipment limited the testing and evalution of control schemes. Essentially all maintenance work at the treatment plant involving the electrical, pipe fitting, and machinest trades is conducted during the day shift. In many instances one or both filters were out of service during the day but operated during the relief and midnight shifts. For this reason the data collection routine was quite sporadic. The following comments address the major problems encountered during the data collection period.

a) filter no. 2 out of service from October 3, 1980 to November 5, 1980
b) belt scale serving filter no. 1 out of service from December 10, 1980 to February 4, 1981
c) analog input card for remote terminal no. 1 out of service from April 9, 1981 to May 14, 1981
d) maintenance work on filter no. 1 limited computer control hours in February and March, 1981
e) software modification and debug limited computer control hours from December, 1980 to June, 1981

B. ROUTINE DATA

1. Combined Data Sets

During the 12-month period, July, 1980 through June, 1981, approximately 2800 hourly average data sets were generated. These data sets were divided into three main categories as follows: (a) filter no. 1 under computer control, (b) filter no. 1 under manual control, and (c) filter no. 2. In addition each category was subdivided into complete and partial data sets for further analysis. This section deals with the analysis of the combined (complete + partial) data sets.

Filter performance for the three modes is summarized in TABLE 14. These data demonstrate that, on the average, filter no. 1 under computer control processed more sludge with lower chemical doses. If it is assumed that the average raw sludge solids did not vary for the three categories, then the computer control mode also produced a drier cake.

During the period of data collection a number of computer control strategies were utilized for controlling the filter yield (in terms of wet weight/hr.), the vat level, and the $FeCl_3$ dose. During the entire period however, the lime dose was always controlled through a manually entered pH setpoint. It appears that the major advantage of the computer mode is to substantially reduce the average lime dose.

The data presented in TABLE 14 indicate the possibility of bias because the average sludge feed for the two manual modes varies substantially. It is

TABLE 12. COMPLETE DATA SETS FOR FILTERS 1 AND 2

Parameter	Symbol	Filter 1	Filter 2
Date	-	yes	yes
Hour	-	yes	yes
Raw Sludge			
Flow	FLOW	yes	yes
Solids	SSR	yes	yes
pH	PHR	yes	no
ORP	ORPR	yes	no
Ferric Conditioned Sludge			
pH	PHF	yes	no
ORP	ORPF	yes	no
%$FeCl_3$	PF	yes	yes
Lime Conditioned Sludge			
pH	PHL	yes	no
%CaO	PL	yes	yes
Filter			
Vat level	VAT	yes	yes
Vacuum	VAC	yes	yes
Drum Speed	DRUM	yes	yes
Wet Cake Rate	TON	yes	yes
Hours Since Cloth Cleaned	CLOTH	yes	no
Cake Solids	SSF	yes	yes
Cake Volatile Solids	VOLS	yes	yes

possible that the operators became accustomed to higher flows to filter no. 1 during the computer control mode and thus maintained them during manual control. The frequency distributions presented in Figure 33 demonstrate that the variability of the sludge feed was considerably greater for filter no. 1 under manual control than for the other two modes. This does not support the hypothesis of bias; however, it is possible that only a portion of the operators were affected.

The data summarized in Figures 34, 35, and 36 demonstrate that, although the variability of wet cake yield was essentially the same, the variability of chemical feed was considerably greater in the manual modes. This is especially true for lime. These data support the earlier observation that control of the lime dose was the major advantage of the computer control mode.

2. Complete Data Sets

The complete data sets, as described in TABLE 12, are a subset of the

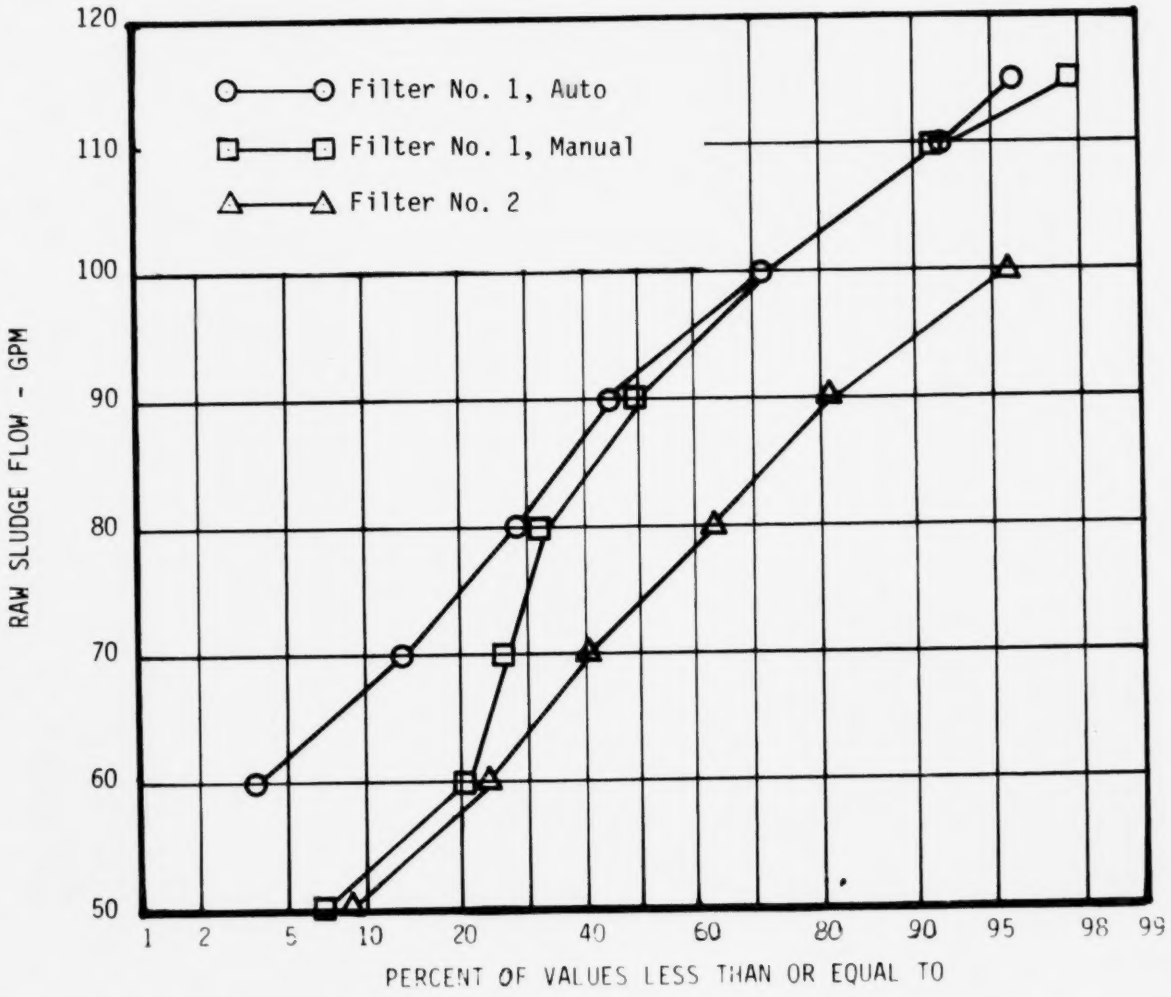


Figure 33. Frequency distributions for raw sludge flow for all data sets.

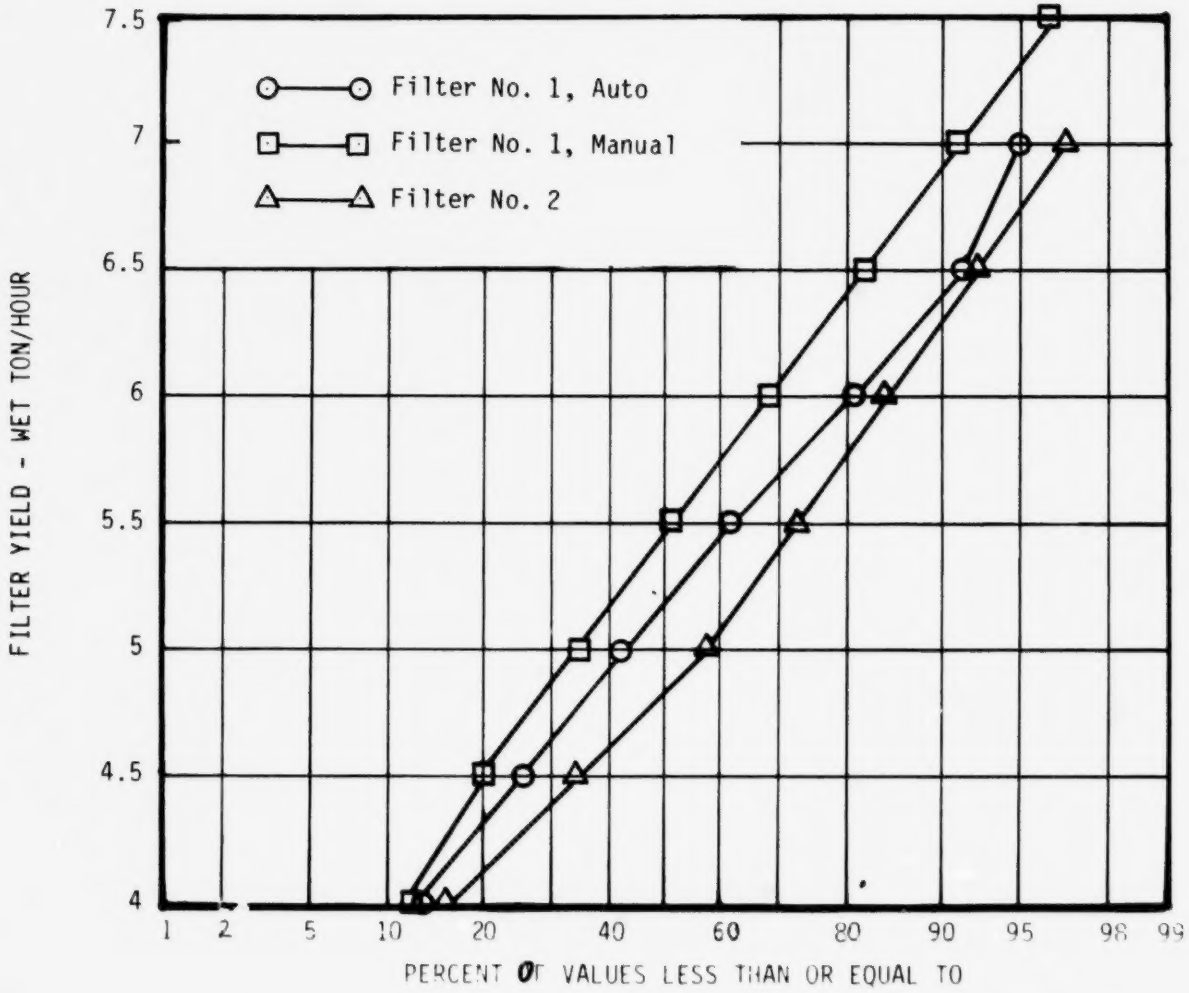


Figure 34, Frequency distributions for filter yield for all data sets.

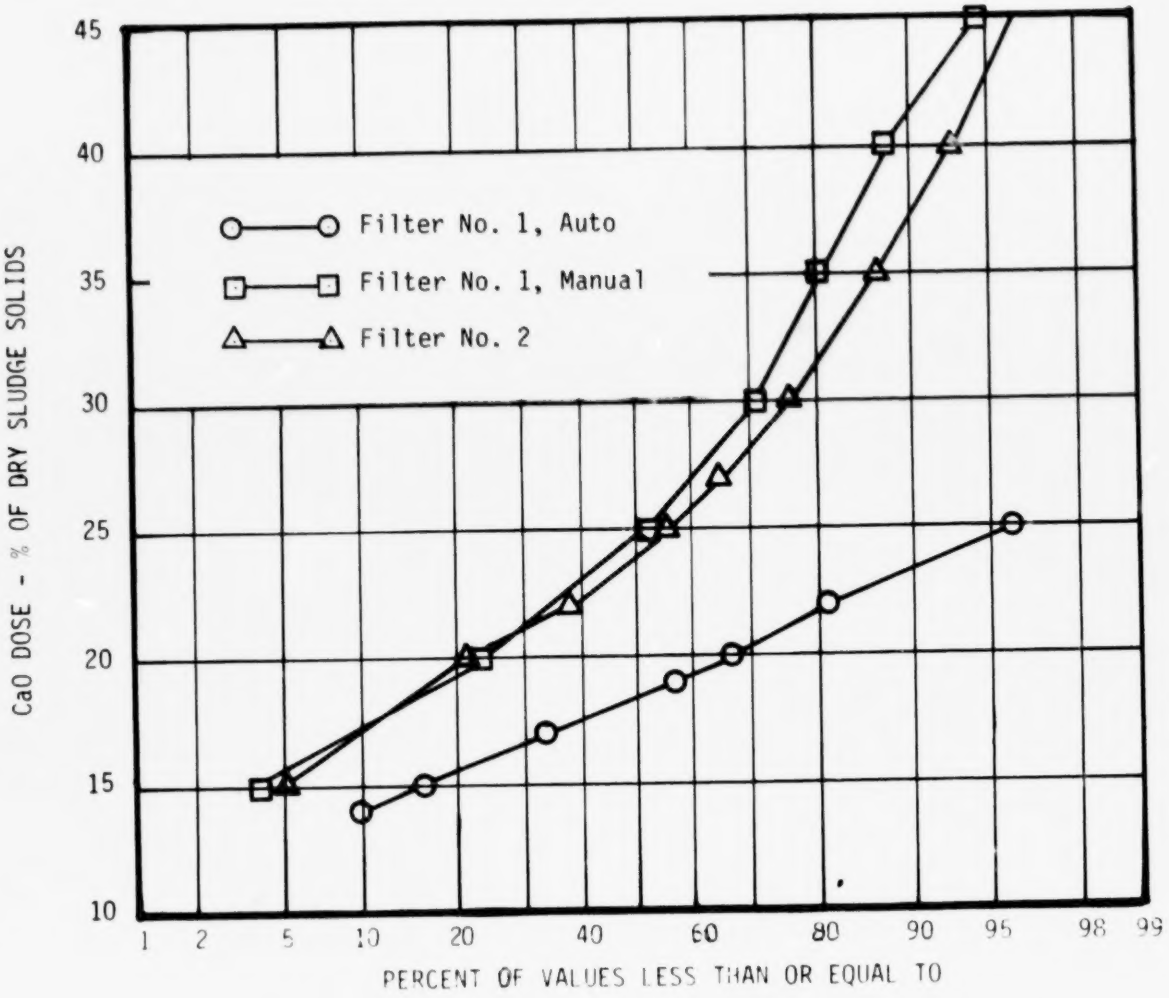


Figure 35. Frequency distributions for lime dose for all data sets.

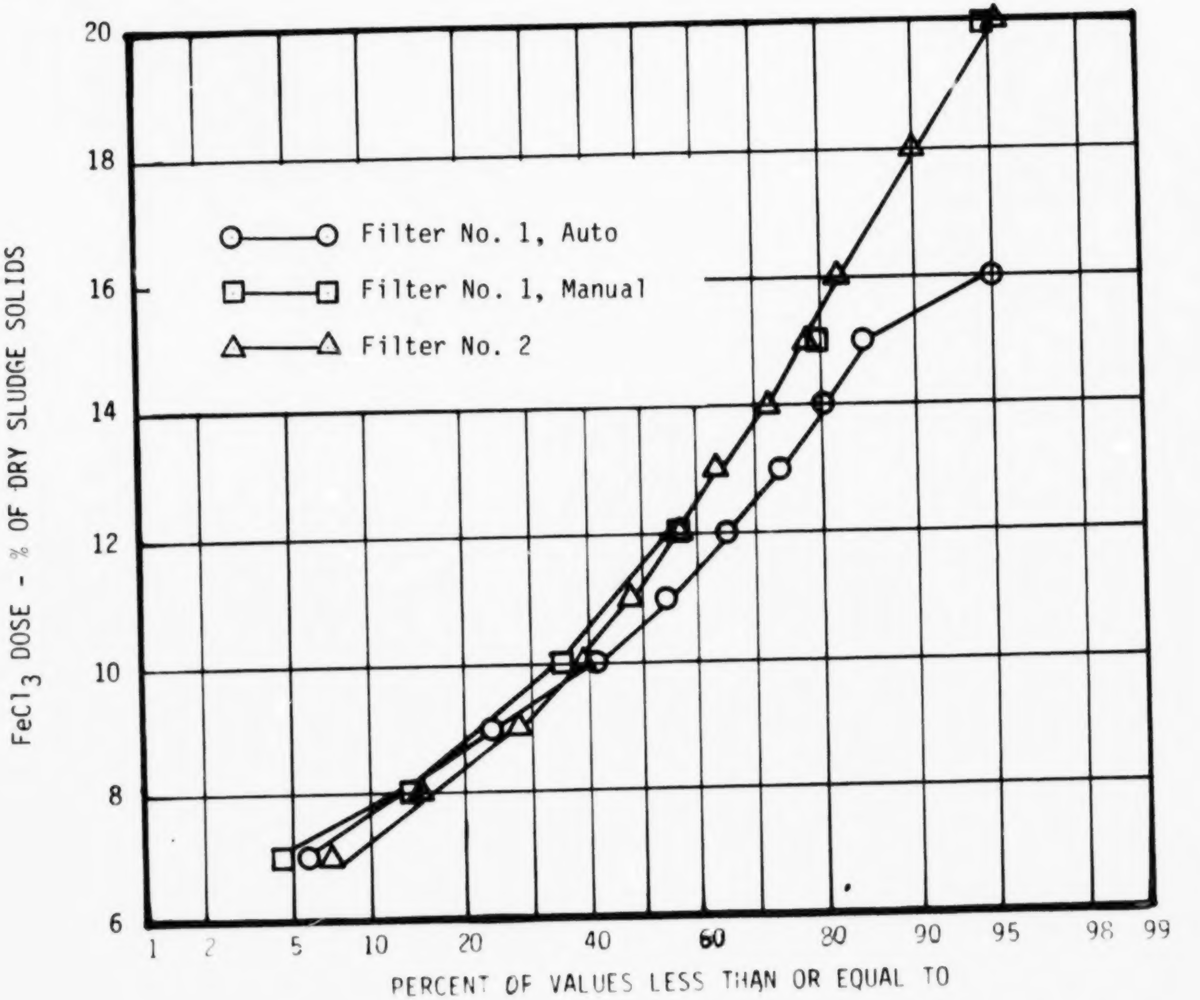


Figure 36. Frequency distributions for $FeCl_3$ dose for all data sets.

TABLE 13. MONITORED FILTER OPERATION - TOTAL HOURS

Month	Filter No. 1		Filter No. 2
	Manual	Computer	
July (1980)	-	15	-
August	-	12	-
September	93	127	190
October	300	167	34
November	133	15	102
December	98	7	190
January (1981)	-	-	-
February	122	2	97
March	112	32	138
April	19	55	79
May	129	-	43
June	241	54	210
TOTAL	1,247	486	1,083

approximately 2800 observations discussed in the previous section. These data sets include all hourly averages for which a cake solids analysis was available. The summary presented in TABLE 15 again indicates that the major advantage of computer control was the decreased lime dose with the associated increase in cake volatile content.

The last two parameters listed in TABLE 15 do not describe performance but do affect it. Under computer control the vat level was controlled by adjusting the raw sludge feed rate. The level setpoint was determined using equation [16]; and, in some cases was fixed by setting $K_8 = 0$. Under manual control the sludge feed rate was fixed and the vat level responded to changes in dewatering rates as well as changes in the sludge feed rate.

The data presented in TABLE 15 support the hypothesis of operator bias in terms of sludge feed rates. It appears that at least some of the operators chose not to treat both filters the same under manual control. The distribution of flows presented in Figure 37 also support this contention. For this reason the remaining analyses will be based on comparisons of filter no. 1 computer mode vs filter no. 2.

In terms of incineration operation the ratio of water:volatiles is an important variable both in terms of fuel consumption and maintaining steady hearth temperatures. The frequency distributions presented in Figure 38 demonstrate considerably more variation in this parameter for manual operations. It is interesting to note that the average value for the three-year period of operation 1978-1980 was 7.8. This is approximately equal to the median value observed for filter no. 2. The data presented in Figures 39 to 43 illustrate that the observed variability is directly related to the variability in the chemical feed rates.

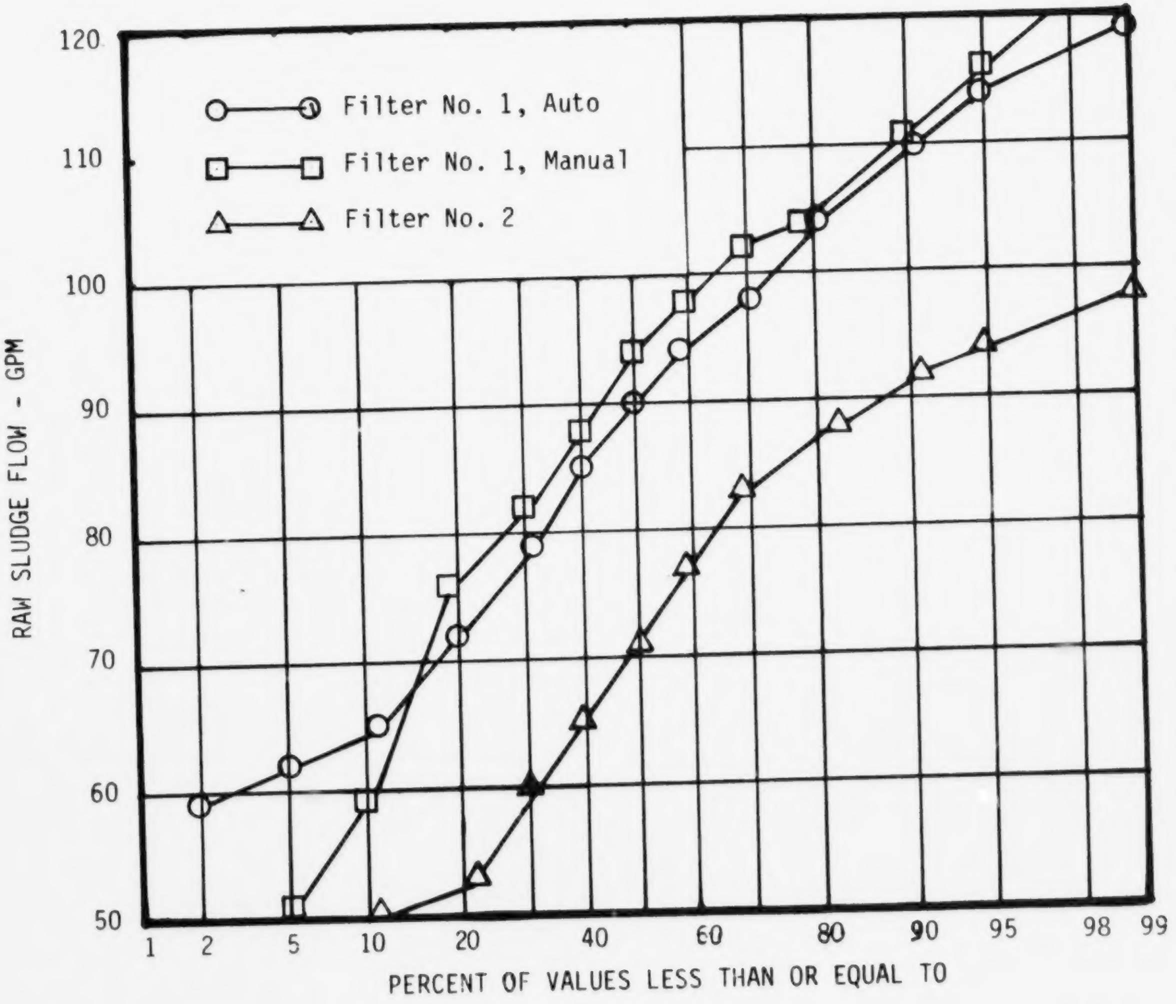


Figure 37. Frequency distributions for raw sludge flow for complete data sets.

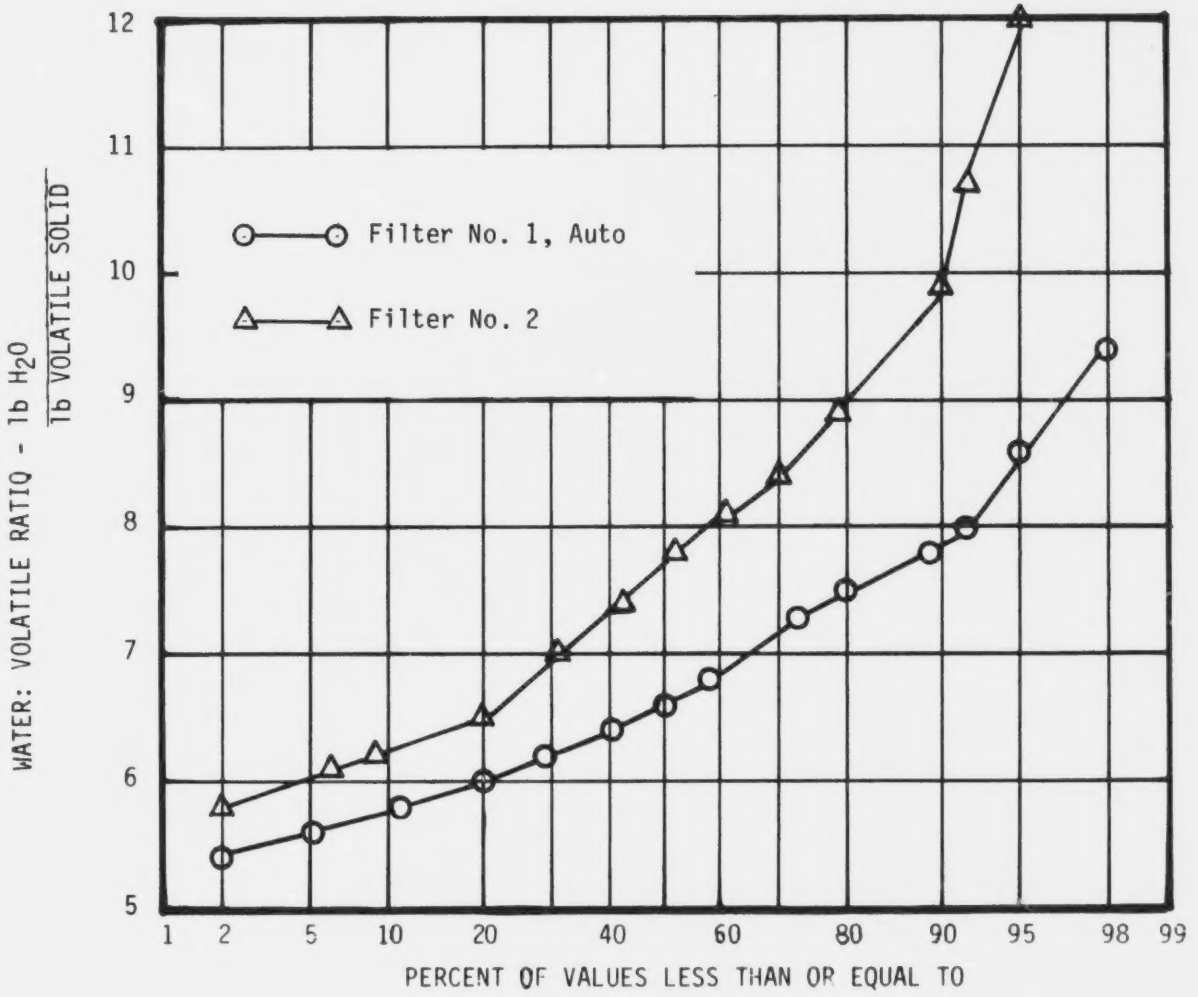


Figure 38. Frequency distributions for water : volatile ratio of cake for complete data sets.

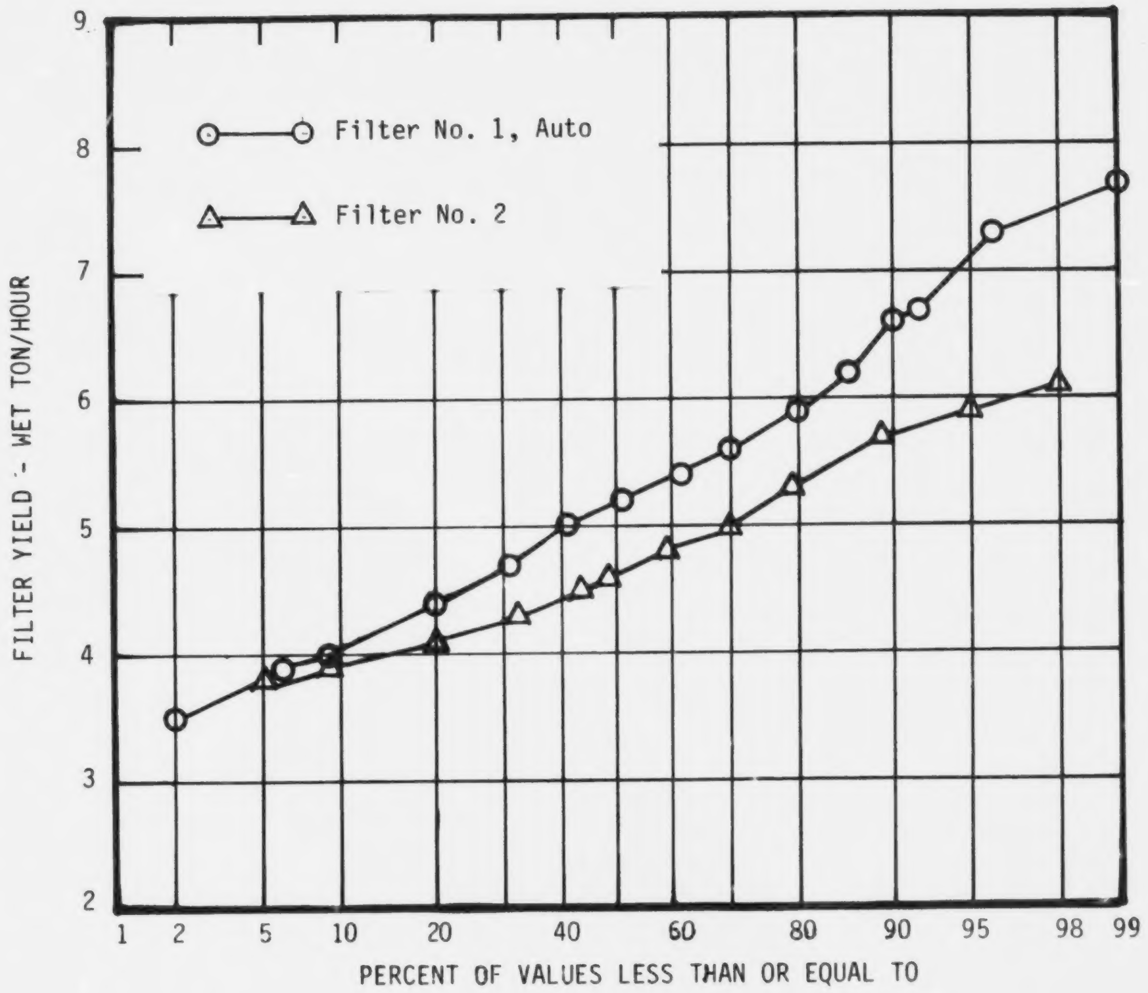


Figure 39, Frequency distribution for filter yield for complete data sets.

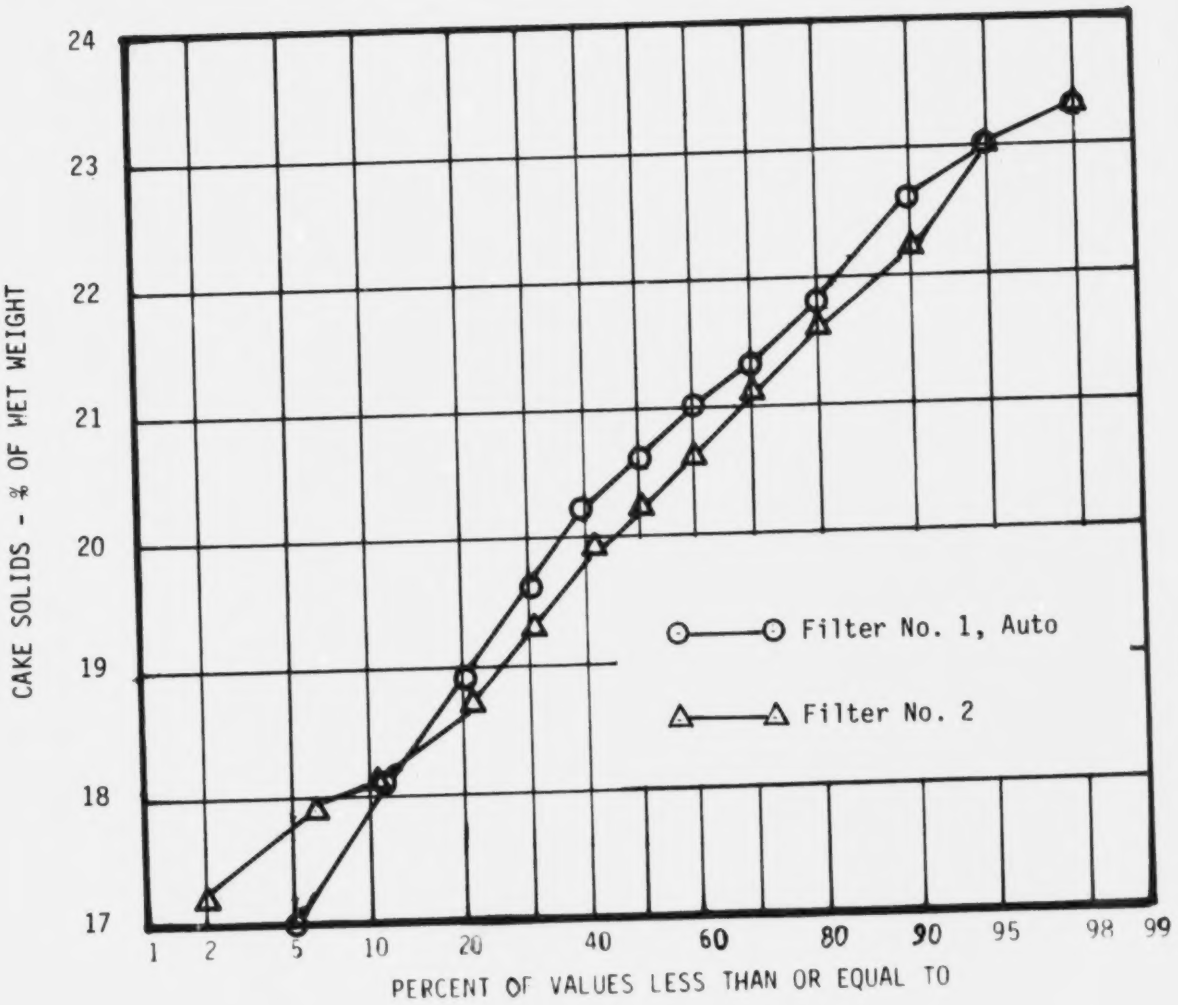


Figure 40. Frequency distributions for cake solids for complete data sets.

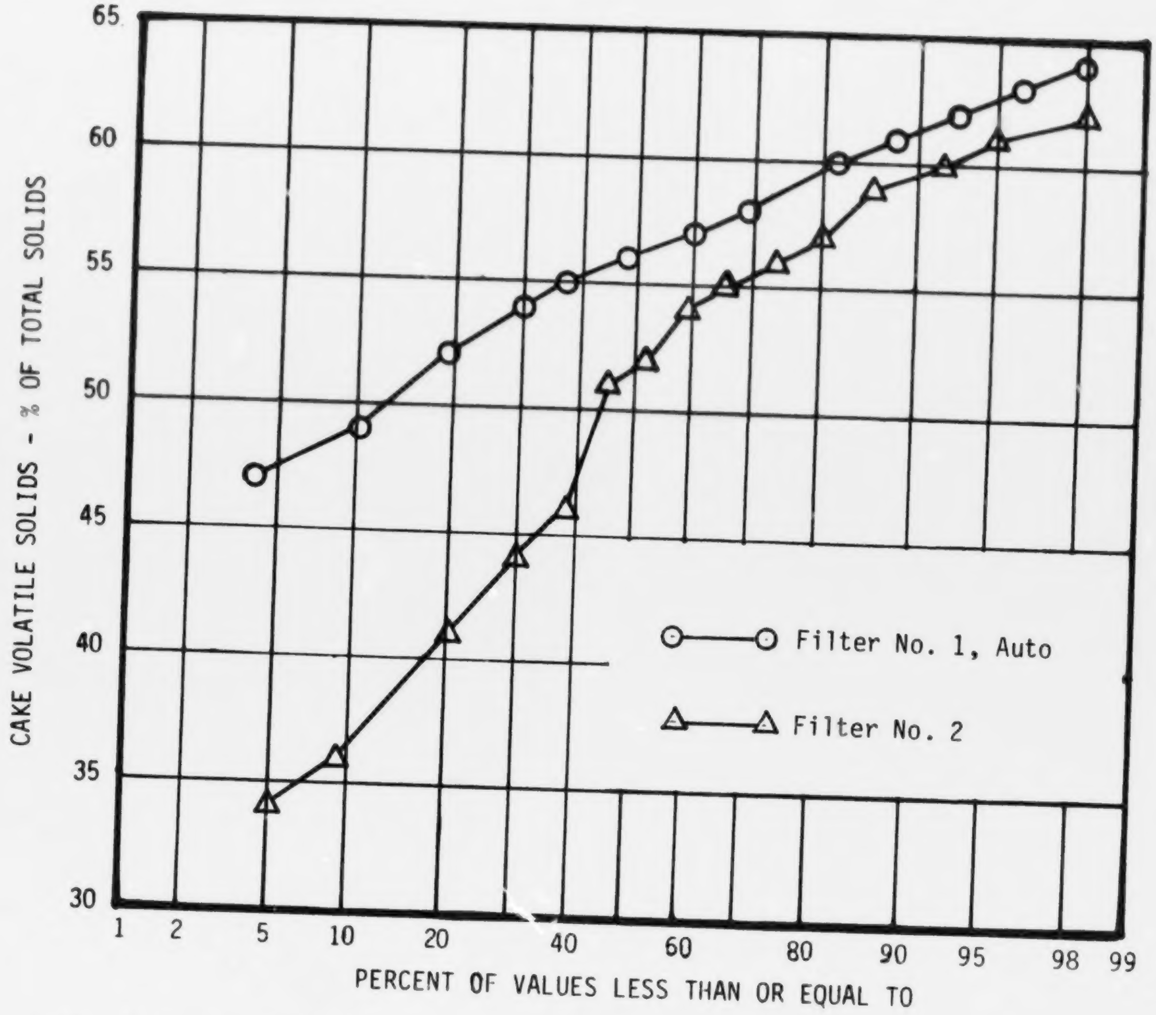


Figure 41. Frequency distributions for cake volatile solids for complete data sets.

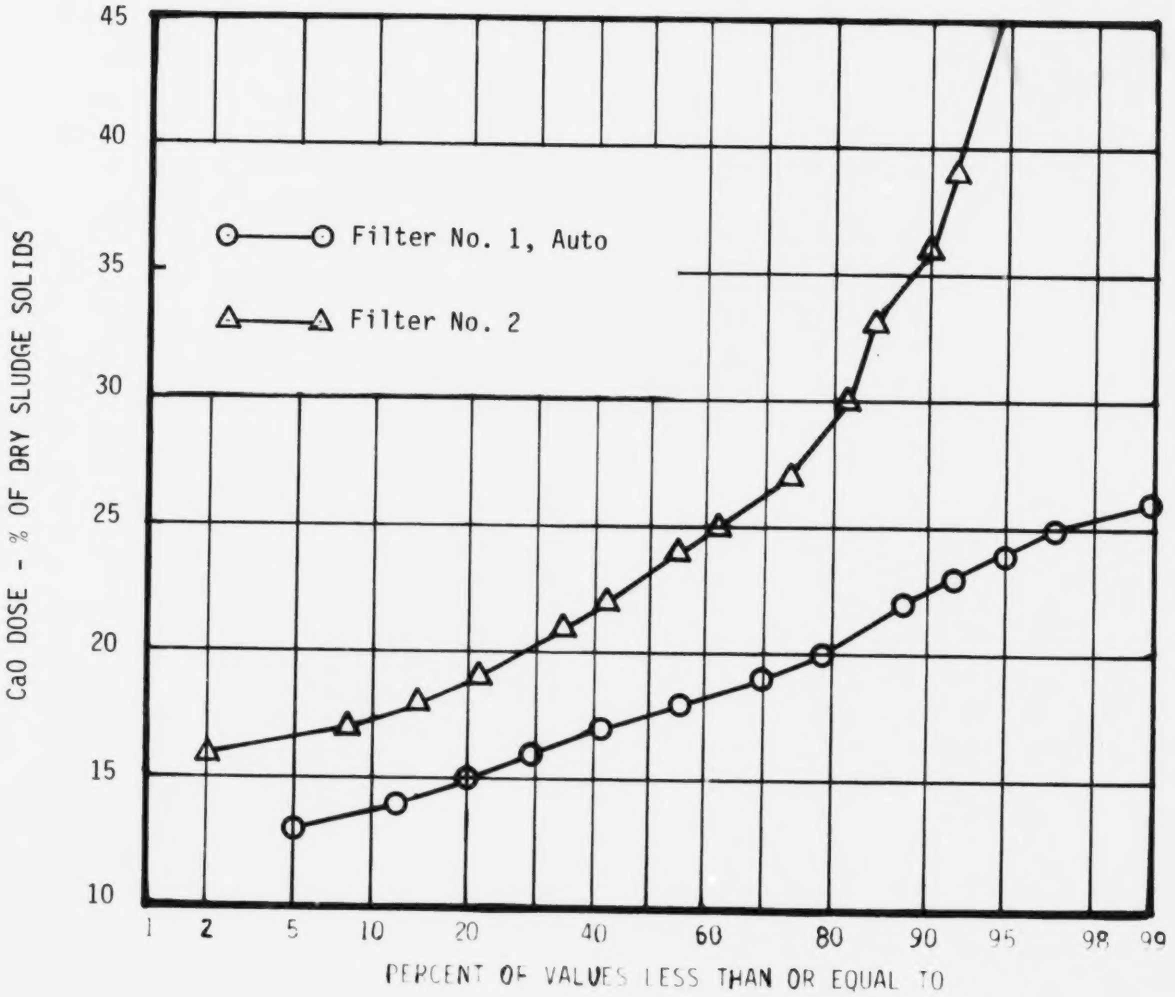


Figure 42. Frequency distributions for lime dose for complete data sets.

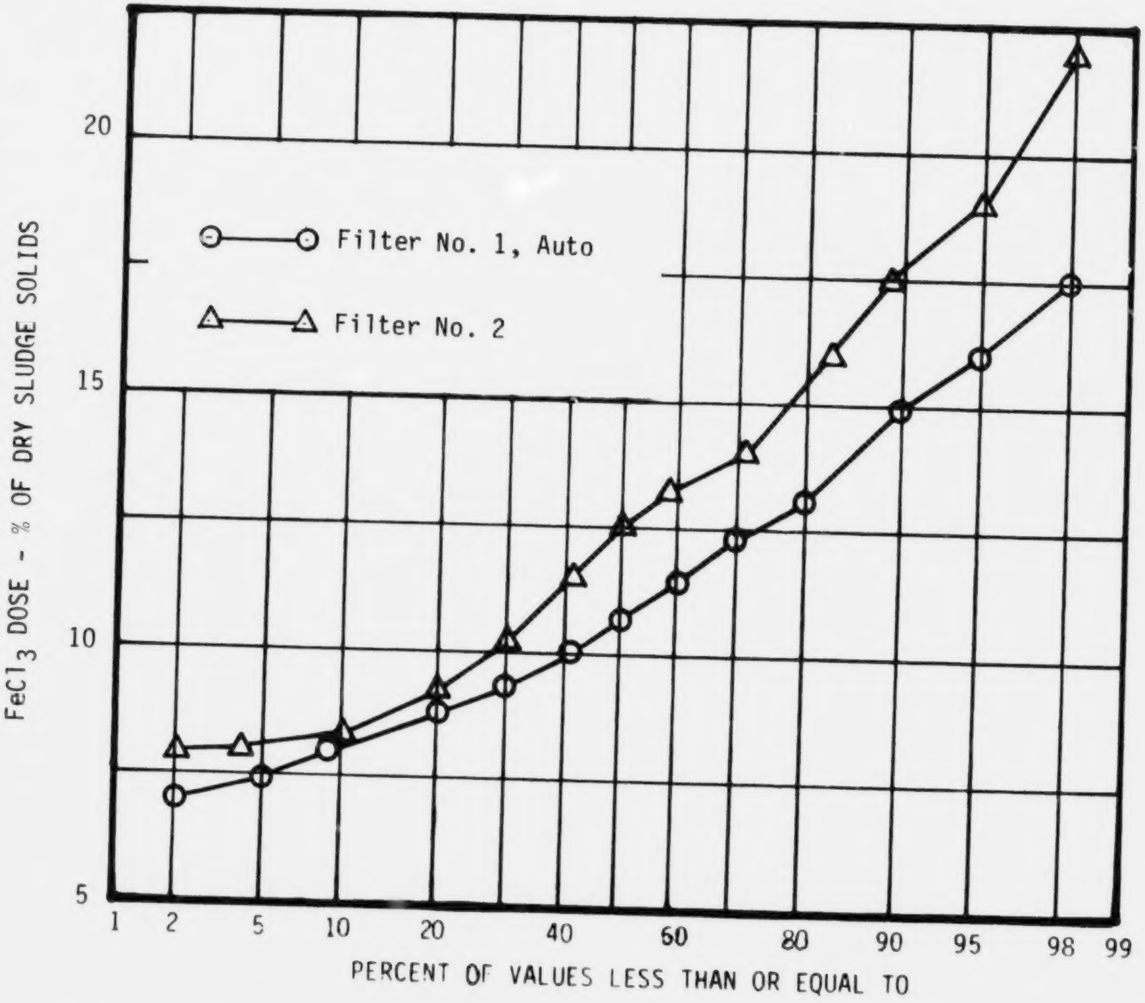


Figure 43. Frequency distributions for $FeCl_3$ dose for complete data sets.

TABLE 14. AVERAGE FILTER PERFORMANCE BY MODE-COMBINED SETS

Parameter	Filter No. 1		Filter No. 2
	Computer	Manual	
Sludge feed- l/s (gpm)	5.7 (90)	5.4 (86)	4.7 (74)
Cake yield - wet mt/hr (ton/hr)	4.7 (5.2)	5 (5.5)	4.5 (5.0)
$FeCl_3$ - % of sludge solids	11.5	12.1	12.1
CaO - % of sludge solids	19.0	27.1	26.0

TABLE 15. AVERAGE FILTER PERFORMANCE BY MODE - COMPLETE SETS

Parameter	Filter No. 1		Filter No. 2
	Computer	Manual	
Sludge feed - l/s (gpm)	5.6 (89)	5.7 (90)	4.5 (71)
Cake yield - mt/hr (ton/hr)	4.8 (5.3)	5.2 (5.7)	4.4 (4.8)
Cake solids - %	20.5	20.8	20.3
Volatile solids - %	56	48	50
$FeCl_3$ - % of sludge solids	11.2	11.5	12.9
CaO - % of sludge solids	18.3	24.3	26.0
pH of ferric cond. sludge	4.9	4.8	-
pH of lime cond. sludge	12.0	12.1	-
lb H_2O/lb Volatile	6.9	8.0	8.1
Vat level - cm (in)	43 (17.1)	53 (21)	37 (14.8)
Drum Speed - RPH	15.3	15.3	13.3

C. PARALLEL TEST

1. General

In April, 1981 a test was conducted over a four-day period to compare manual and automated control of the sludge conditioning and vacuum filtration processes. The scheduling was based primarily on the projected availability of both filters and incinerators. The parallel test was initiated at 1500 hrs. April 6 and ran for 68 hours until 1100 hrs April 9 when an ash line plug required a shutdown of the building. Both filters were taken out of service for several hours during the test because of typical operating problems. In addition, some problems were encountered with the process control computer which required manual intervention.

The media of both filters no. 1 and no. 2 were acid cleaned on April 5, the day before the test was initiated. Both filters drew sludge from the same holding tank and from the same level. Filter no. 2 was run at the discretion of the operators throughout the test.

2. Data Collection

In addition to the continuous data collected by the monitors and summarized on the hourly reports, grab samples were collected from both process trains to provide additional comparisons. Cake samples were collected once per hour and the total and volatile solids determined. A raw sludge sample was collected once per shift (8 hr); and, the solids content was determined to check the calibration of the solids analyzer. At approximately 1700 hr. on April 17, test hour 27, the solids analyzer serving train no. 2 failed (piston drive motor). The value of SSR for train no. 2 was thereafter assumed to be equal to that for train no. 1.

Samples of the lime conditioned sludge, from both trains, were collected each shift. The specific resistance (SR) was determined to characterize dewaterability. In addition, the concentration of the ferric chloride and lime feed streams were monitored throughout the test period.

3. Setpoint Chronology

The purpose of process automation is generally to increase efficiency and/or reduce operator time and effort. The ultimate control system would require the operator only to enter the setpoint for product output. Because of the limited understanding of the sludge conditioning process this goal was not reached during the project. As a result a number of setpoints are required for the control scheme ultimately used. In addition, the methods used to calculate setpoints, Section 10.D, require operator judgement. Because of this a number of setpoint changes were made throughout the period. The status of the various setpoints is summarized in TABLES 16, 17, and 18.

During the first two days of the test, it was periodically required to manually control the ferric chloride addition. When the drum speed reached its upper limit and the production rate was below setpoint, ferric overdosing occurred. The problem was remedied by returning the drum to manual control for a short period and reducing its speed. A dose limit of 13% was eventually instituted to eliminate this problem.

4. Results

The specific resistance analyses of the conditioned sludges, summarized in TABLE 19, demonstrated that, on the average, train No. 1 (auto) did a better job of chemical conditioning. The significance of this difference is not readily apparent; however, in the five sets (1,3,4,7,10) where the train no. 2 resistance was greater than train 1 by more than 0.7, the cake production rate for train 2 fell below train 1 for the hour of the grab sample.

The average performance of the two sludge dewatering trains is characterized in TABLE 20. The hourly observations are summarized in Appendix B. On the average train no. 1 performed only slightly better than train no. 2. The increase in total solids can be attributed to the higher drum speed which produces a thinner, dryer cake, whereas, the increase in volatile solids content is related to the slightly lower lime dose achieved with automated control.

TABLE 16. $FeCl_3$ CONTROL SETPOINT - APRIL TEST

Test Hour*	Strategy	Setpoint	Comments
1 - 2	CST	0.5SSR + 8	Drum at max speed; ratio mode (dose) selected automatically, ratio control not functioning properly.
3 - 5	pH	5.4	Restart with pH mode following program edit.
6 - 9	CST	10SSR - 10	Could not attain pH of 5.4.
10 - 12	CST	10SSR - 14	Decreased setpoint to match predicted value.
13 - 18	Manual	--	Problem with ratio mode interrupting CST control.
19 - 20½	CST	10SSR - 14	Restart in CST mode.
20½ - 22	Ratio	0.11 x sludge mass flow	Trial run of ratio control; not functioning properly.
23	Filter out of service		
24	CST	10SSR - 14	Restart in CST mode.
25 - 26	pH	4.6	Setpoint PHF generated by CST control could not be attained.
27 - 28	pH	5.0	Previous setpoint too low, could not be attained.
29 - 36	CST	10SSR - 11	Previous control working, arbitrarily changed.
37-41	Manual	---	Computer down and restarted; thin cake, filter unstable.
42	Δ pH	PHF = 0.04 [25(PHR - 4) + 5 SSR - 30] + 3	
43	Δ pH	PHF = 0.04 [25(PHR - 4) + 9 SSR - 30] + 3	
44-45	Filter out of service		
46-47	Δ pH	PHF = 0.04 [25(PHR - 4) + 9 SSR - 30] + 3	

Continue TABLE 16. $FeCl_3$ CONTROL SETPOINT - APRIL TEST

Test Hour*	Strategy	Setpoint	Comments
48-49	ΔpH	$PHF = 0.04 [25(PHR - 4) + 9 SSR - 25] + 3$, adjusted K_4 to increase setpoint	
50-56	ΔpH	$PHF = 0.04 [25(PHR - 4) + 9 SSR - 30] + 3$ readjusted K_4 to previous level. PHF was too high causing $FeCl_3$ pump to run slow. $FeCl_3$ dose down to 6% prior to adjustment.	
57	pH	5.0	Manual pH setpoint following computer shutdown/startup.
58 - 59	pH	4.8	Setpoint reduced to match PHF and maintain dose.
60 - 61	pH	4.4	Setpoint reduced because of decrease in raw sludge solids concentration (SSR).
62 - 68	pH	4.6	Adjust setpoint after computer shutdown/startup.

* Test initiated 1500 hr. April 6, 1981

All of the data collected previous to this test indicated that the lime dose under manual control would average closer to 30% than 20%. Although the plant operators were not given any special instructions during this test there is a remote possibility they were competing with the computer. Based on observations during the test and the previous lack of concern this explanation is judged to be remote. Unfortunately, after the test was completed it was determined that the pump supplying lime slurry to train no. 2 was severely worn and was pumping near capacity during the entire test. The average speed setting of the manually controlled pump was approximately 90% full scale whereas the computer controlled pump usually operated at 50% full scale. The operators typically operated the lime pump near maximum speed.

Previous experience indicated pumping rates less than 50% full scale led to sedimentation in the lime piping and eventually plugging. For this reason the lime pump speed control was limited to adjustments in the range of 50% to 100% full scale. In retrospect if the lime slurry had been adjusted to a lower solids content this problem may have been eliminated.

Because of the problem with the lime pump, the data collected during the test are compared to more typical data in TABLE 21. Typical manual operation produces a cake with a much lower volatile content and uses considerably more lime to do so. The chemical costs presented are based on MWCC contracts in force during the summer of 1981. The total cost for chemical conditioning for train no. 1 was approximately $1.90/mt ($1.80/ton) sludge solids less than for train no. 2 during the test; however, the savings increase to approximately 6.06/mt ($5.50/ton) when the five-year averages are considered. The estimated annual savings fall in the range of approximately $16,500 to $50,600.

TABLE 17. VAT LEVEL SETPOINT - APRIL TEST

Test Hour*	Setpoint-inches	Comments
0 - 8	5 + 36 (0.5 - THICK)	
9 - 16	12 (fixed)	lowered vat level to decrease thickness.
17 - 20	5 + 18 (1 - THICK)	Increased vat level because of low SSR.
21 - 28	5 + 36 (0.55 - THICK)	Increased response to thickness (out of service 22-23).
29 - 42	5 + 36 (0.48 - THICK)	
43 - 59	5 + 36 (0.52 - THICK)	Level getting too low, increase setpoint.
60 - 61	5 + 36 (0.6 - THICK)	Increased vat level because of low SSR.
62 - 68	5 + 36 (0.52 - THICK)	Reduce vat level for normal operation.

NOTE: THICK = cake thickness in inches.
* Test initiated 1500 hr April 6, 1981

The performance level of the two trains is presented in more detail in Figures 44 to 49. Train no. 1 was consistently more efficient in terms of sludge volume processed, dry solids yield, and volatile solids yield. Figure 49 compares cake quality in terms of heat deficit or auxiliary heat required for combustion. The heat deficit was estimated using a model previously developed for the Seneca incinerators (9). The heat value of the cake was assumed to be 21,900 kJ/kg (9400 BTU/lb) volatile solids. The average difference in heat deficit for the two trains was approximately 186 kJ/kg (80 BTU/lb). This amounts to a savings of approximately 5m^3/mt (160 ft^3/ton) natural gas or 4.8 l/mt (1.15 gal/ton) fuel oil, both on a wet cake basis.

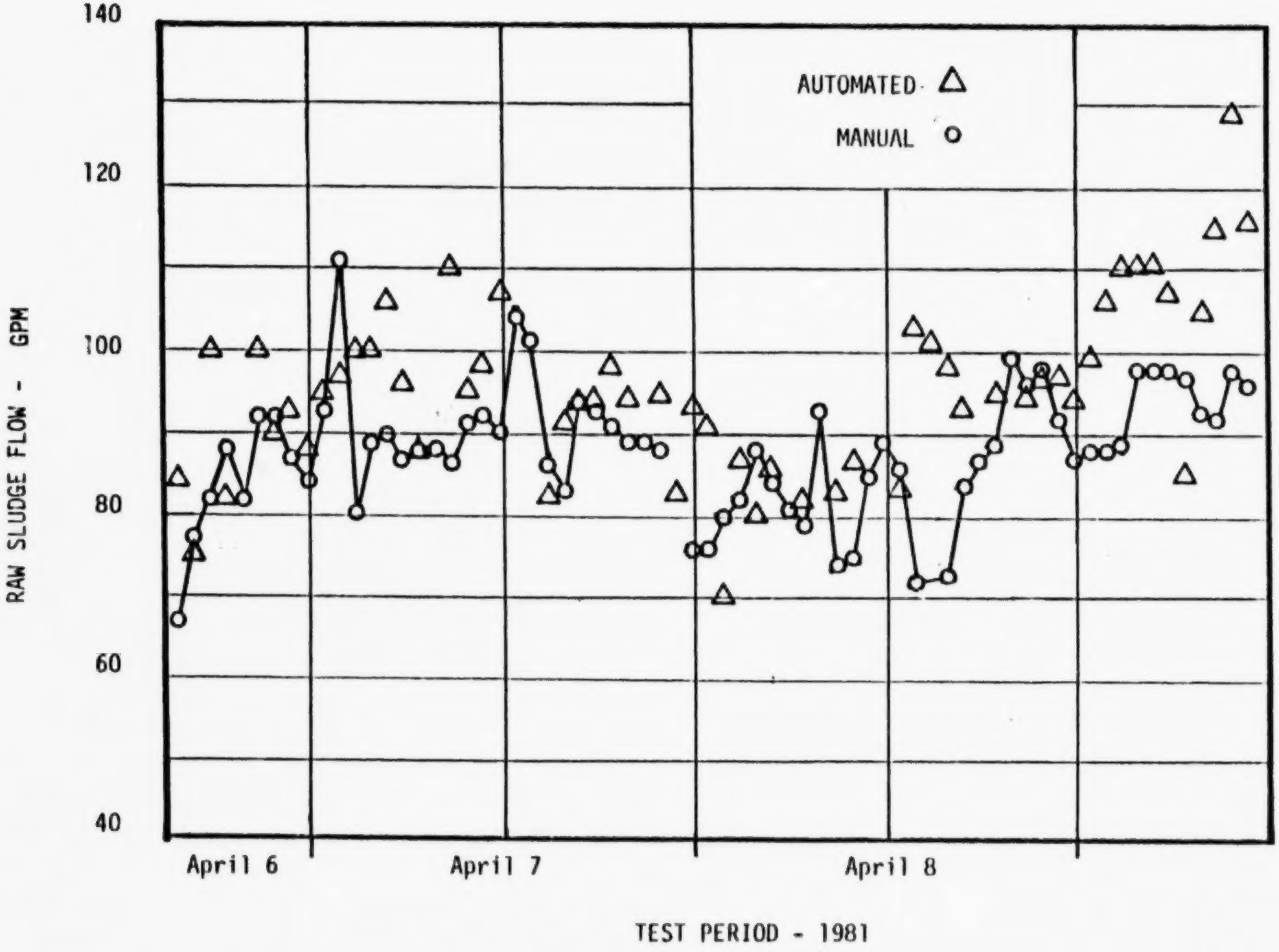


Figure 44. Raw sludge flow to automated and manually controlled filters.

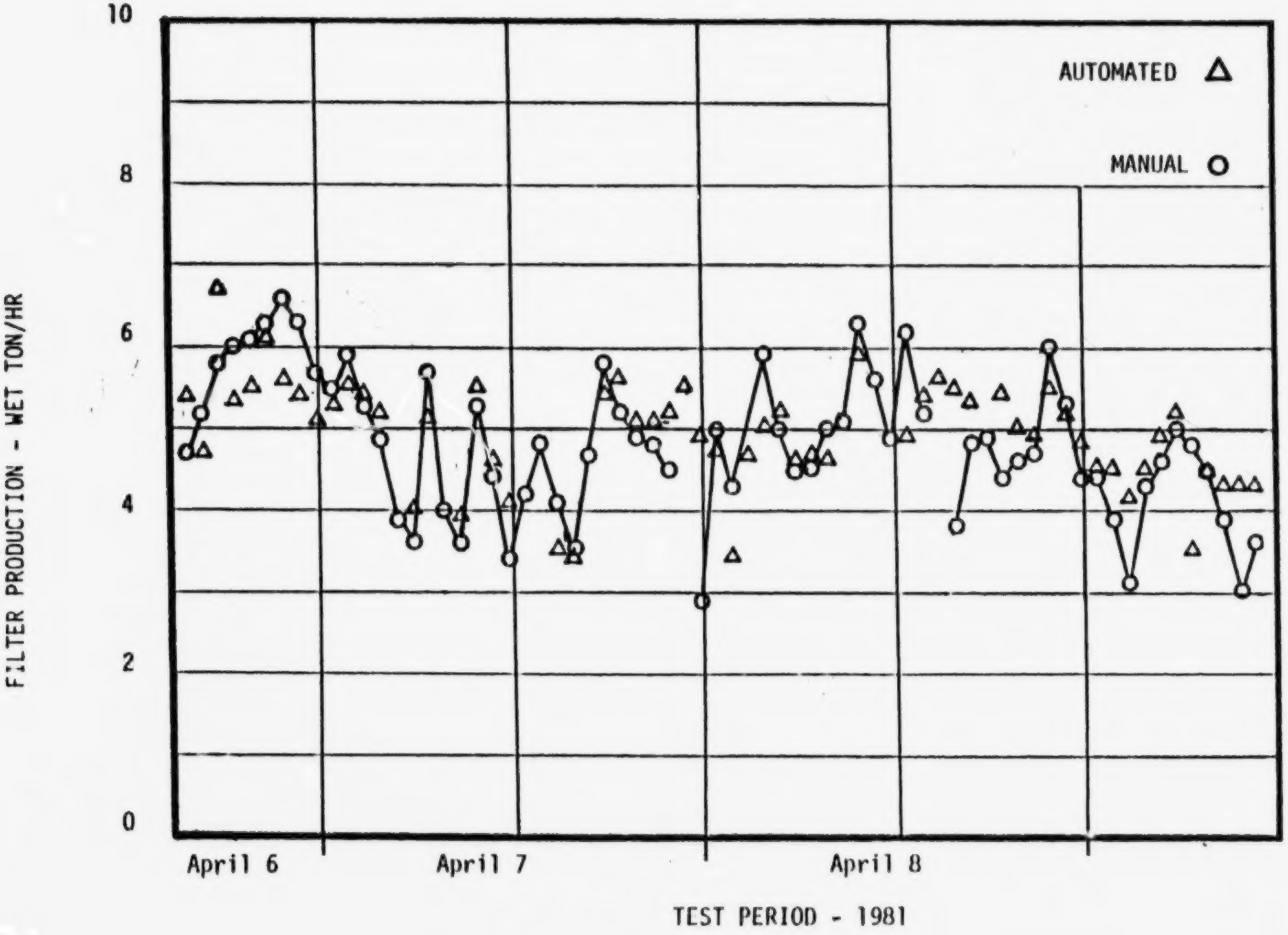


Figure 45. Filter cake production for automated and manually controlled filters.

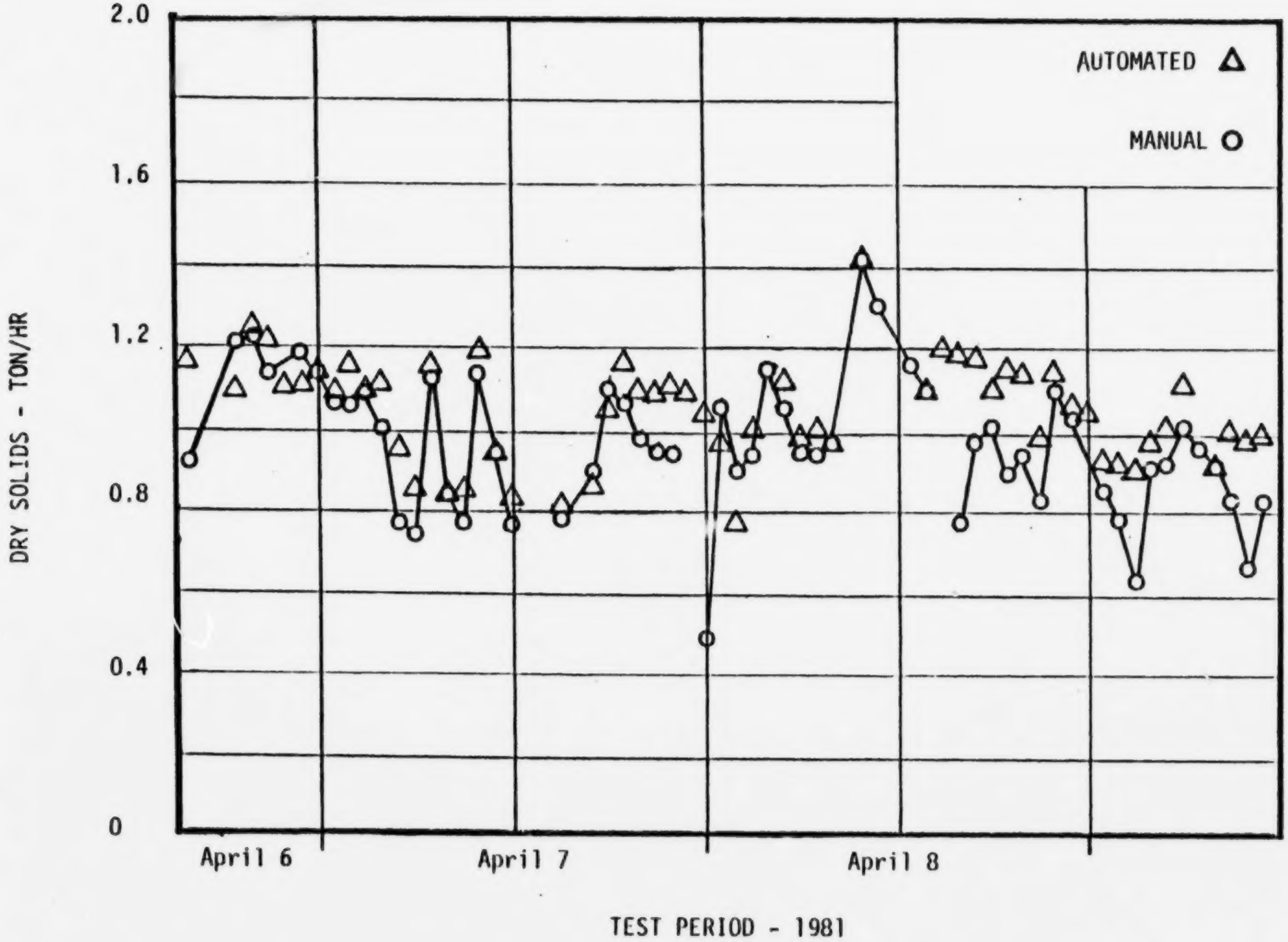


Figure 46. Dry solids production for automated and manually controlled filters.

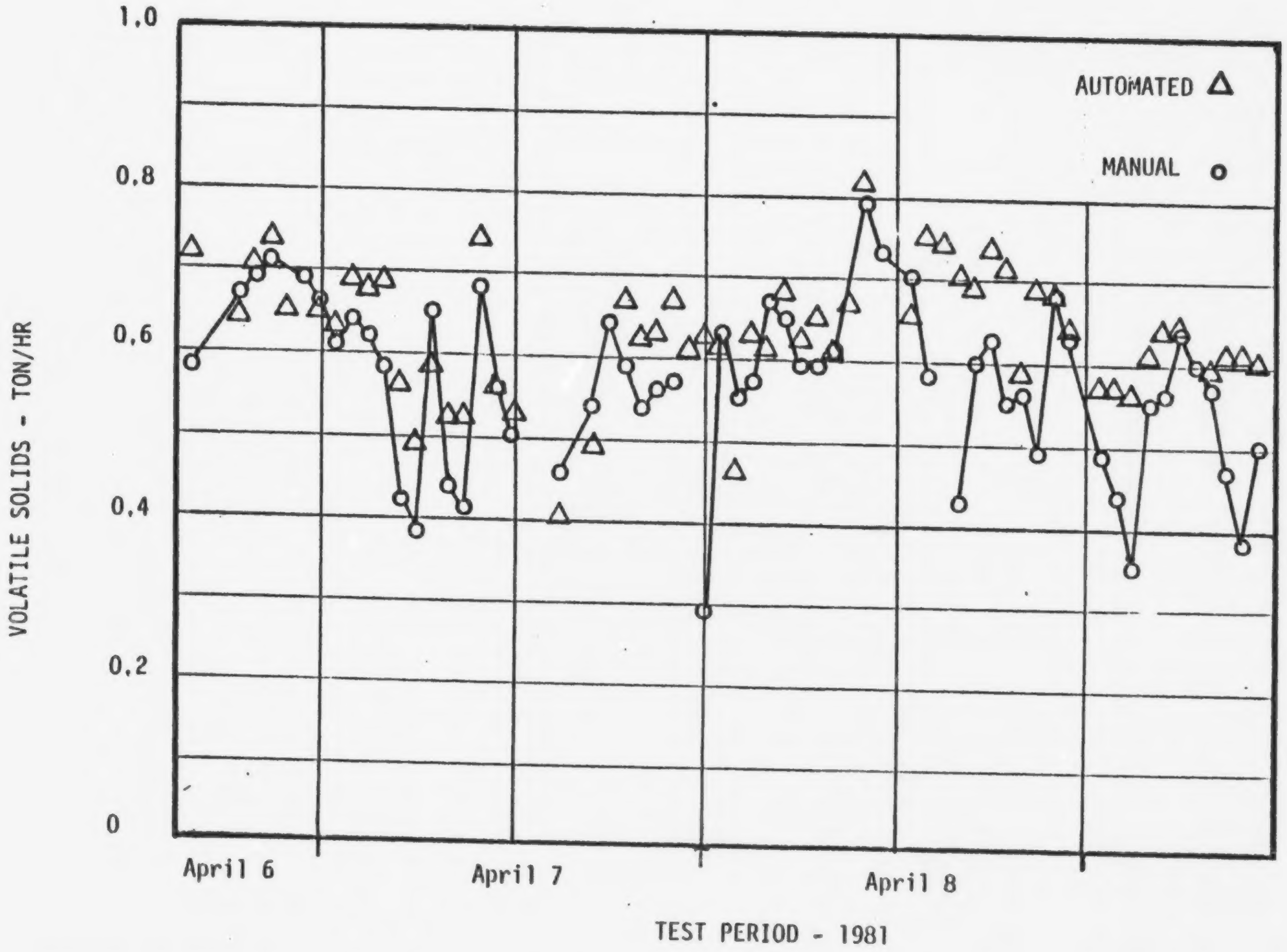


Figure 47. Volatile solids production rate for automated and manually controlled filters.

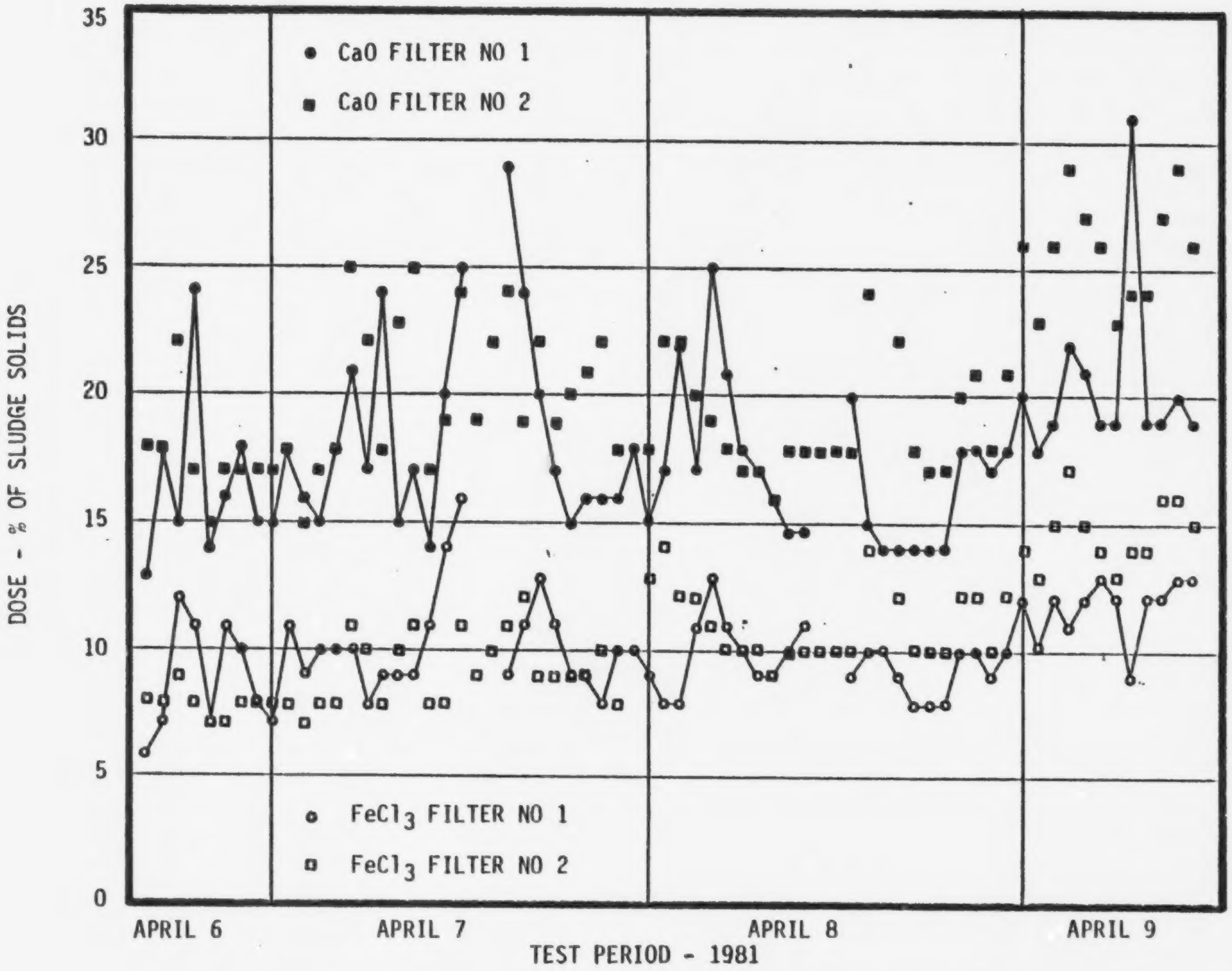


Figure 48. Chemical doses for automated and manually controlled filters.

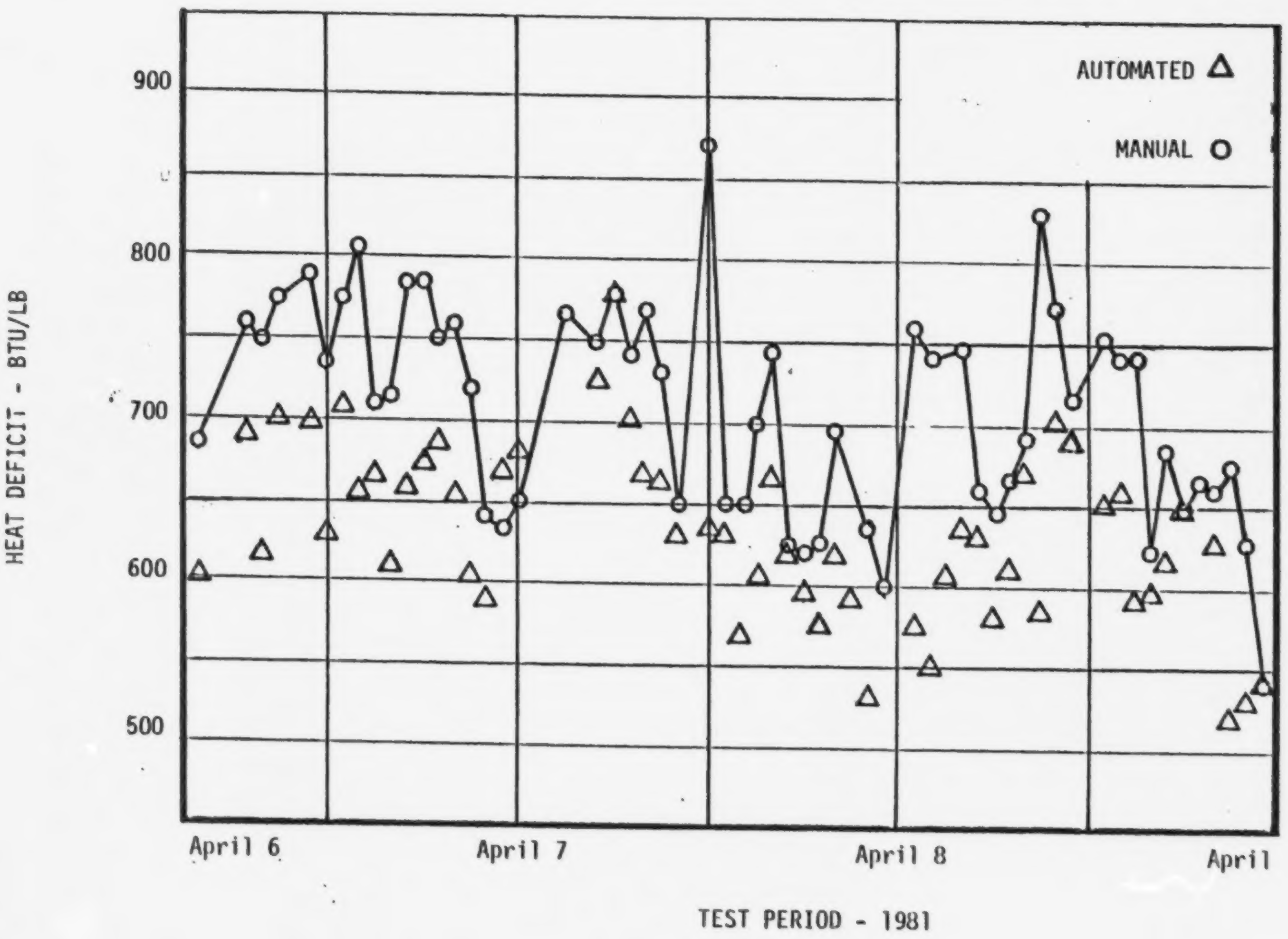


Figure 49. Heat required for combustion of cakes produced on automated and manually controlled filters.

TABLE 18. CAKE PRODUCTION SETPOINT - APRIL TEST

Test Hour*	Setpoint-ton/hr	Comments
0 - 5	6.0	
6 - 8	2 + (1 x SSR)	Adjusted setpoint to decrease drum speed.
9 - 13	5.5	Previous variable setpoint exceeding 6 TPH due to increase in sludge solids.
14 - 21	4 to 5.5	Several changes made; unstable operation due to changes in ferric control, and sludge characteristics.
22 - 23	--	Filter out of service--lime line plugged.
24 - 42	5.25	Stable operation.
43 - 47	6.0	Exceeding 6 TPH at previous setpoint due to increase in sludge solids.
48 - 59	5.25	Excessive drum speed at previous setpoint.
60 - 66	4.75	Excessive drum speed at previous setpoint due to low solids content of sludge.
67 - 68	2 + (1 SSR)	Lower drum speed to prevent upsets due to very thin sludge.

* Test initiated 1500 hr April 6, 1981

Using 1981 unit costs this corresponds to a savings in the range of approximately $0.16 to $1.21 per mt ($0.15 to $1.10 per ton) depending on the fuel used. If the cake solids are assumed to be approximately 25%; and, approximately 75% of the cake solids are sludge solids the potential annual savings falls in the range of approximately $8,000 to $55,000. This range is conservative because the volatile solids content of the cake produced in train no. 2 was considerably higher than normal.

TABLE 19. SPECIFIC RESISTANCE OF CONDITIONED SLUDGE

	Specific Resistance x 10^{-11} - mg/kg		
Date	Test No.	Train 1	Train 2
(April, 1981) 6	1	1.8	3.1
	2	1.7	2.1
7	3	2.2	3.5
	4	2.1	3.4
	5	2.2	2.4
8	6	2.3	2.2
	7	1.2	1.9
	8	2.6	2.3
9	9	3.2	2.9
	10	1.6	3.1
Average		2.1	2.7

If the five-year average cake characteristics are considered to be more typical of manual operation, the average heat deficit increases to approximately 314 kJ/kg (135 BTU/lb). For this case the potential savings fall in the range of $13,500 to $85,000. For the past several years about 85% of the energy for incineration has been supplied in the form of natural gas. A realistic estimate of energy savings is thus approximately $25,000 using the unit cost for the summer of 1981.

TABLE 20. PARALLEL TEST PERFORMANCE SUMMARY

	Flow		Sludge	Dose-%		Cake				Drum
Train	l/m	(gpm)	%Solid	$FeCl_3$	CaO	mt/hr	(Ton/hr)	%Solid	%Volatile	RPH
1	360	(95)	3.4	10	18	4.4	(4.9)	21.1	60.0	14.4
2	333	(88)	3.4	10	20	4.3	(4.8)	20.2	58.2	12.2

TABLE 21. COST FOR DEWATERING CHEMICALS

	Sludge Solids		Dose- %		Cake Solids - %		Chemical Cost	
Year	mt	(ton)	$FeCl_3$	CaO	Total	Volatile	$/mt	($/ton)
1976	7,642	(8,425)	8.2	27	23.0	50.5	-	
1977	7,746	(8,540)	6.0	36	24.0	43.2	-	
1978	9,170	(10,110)	5.1	28	24.0	43.3	-	
1979	7,746	(8,540)	9.2	29	21.8	41.8	-	
1980	9,469	(10,440)	10.1	30	22.0	47.5	-	
Average	8,354	(9,210)	7.7	29.8	23.0	45.3	48.33	(43.84)

SECTION 13

INCINERATOR CONTROL

A. GENERAL

After the initial investigation in 1976 and 1977, the probability of finding a moisture analyzer capable of providing accurate cake moisture estimates appeared extremely low. (Further testing indicated that the perception was accurate see Section 6.C.6a) Cake moisture is one of the two parameters used to measure filter performance (the other is wet production) and without it feedback control for cake moisture and/or filter yield is not possible. It was thus obvious that steady state filter operation in terms of cake moisture, yield, or total heat deficit, was not feasible.

Since the input to the incinerator can vary, even with automated control of the dewatering train, some control action is necessary to maintain steady incinerator operation. The primary objective for instituting new incinerator controls was to minimize the use of auxiliary fuel while operating within the constraints of burning all cake produced and meeting stack discharge standards.

The control hardware required for expanding the project to include incinerator control was limited to a second remote terminal (RTU) which provided the communication link between the central processing unit (CPU) and the field instruments and devices. The same CPU and peripherals that were used for control of dewatering were used; however, software changes were made to decrease execution times.

Concurrent with this project the Quality Assurance Section of the Operations Department conducted a series of tests to determine if the Seneca incinerators could be operated at near rated capacity and still meet the stack discharge standard. The results of these tests proved to be the basis of the final simplified control strategy.

B. INITIAL CONCEPTS

1. Control Loops

The initial concept for control of the incinerator consisted of the six control loops listed in Section 5D along with a scrubber control algorithm. The scrubber control was eliminated from consideration because the units were being subjected to a testing and modification program to improve efficiency. The remaining loops are described in the following paragraphs.

Rabble Arm Drive--The purpose of this loop was to adjust the speed of the rabble arm in response to the incinerator loading rate and the changes in the temperature profile; i.e., drying, burning, and cooling zones, as illustrated in Figure 50. The proposed control scheme was based on the fact that the residence time on any hearth is a function of the rabble rate. Previous testing of the Seneca incinerator indicated, however, that an increase in rabble rate may eventually move the burning zone up in the incinerator because the increased agitation of the cake increased the drying rate. This phenomenon was not investigated further because the proposed control required cake moisture as an input. The lack of a suitable cake moisture analyzer caused this control scheme to be withdrawn from consideration.

Coal Feed--During a previous project (9) coal feeding equipment was installed adjacent to incinerator no. 1. A testing program demonstrated that a significant portion (50%-60%) of the fuel oil or gas could be replaced by coal mixed with the filter cake. An initial coal feed control scheme was designed based on the calculated heat deficit of the cake. Since the calculation required cake moisture as an input, it was not possible to implement the control. Coal feed was never used beyond the testing stage because of the significant coal delivery, storage, and handling equipment required for full-scale operation.

Hearth 3, 5, and 6 Burners--The purpose of this control scheme, illustrated in Figure 51 was to provide stable hearth temperatures. The output would be used to control the combustion air valves feeding air to the burners. Fuel flow is, in turn, regulated by the air flow rate. This scheme again used the calculated incinerator load as a feedforward signal. This signal was, however, delayed for each burning hearth to account for process deadtime. The temperatures on the controlled hearths were used as the feedback signals to temperature controllers. The temperature controllers received their set-points from a temperature adjust supervisory program. The output from the temperature controller was combined with the delayed loading signal at adjustable ratios before modifying the air valve position. A burner sequence program would start or stop the burners individually if the temperature requirement exceeded what was achievable using one or two burners. The temperature adjust program would maintain stable temperature control by taking into account the temperature distribution over several hearths and preventing imbalances between hearths.

Hearth 1 Burner--This control, illustrated in Figure 52, is similar to the previous burner control; however, a fixed setpoint temperature of 1200°F was proposed to control odors. In addition three burners were sequenced as needed instead of two. This loop was not implemented because stack odor control was not required at Seneca.

Induced Draft Damper--Two methods of controlling the furnace pressure were initially proposed as illustrated in Figure 53. The first method used three signals, furnace load, furnace draft, and position of atmospheric air damper, combined in adjustable ratios, to calculate the position of the ID fan damper. The second scheme utilized an excess air controller to cascade a setpoint to the pressure controller. A simplified version of the first loop was

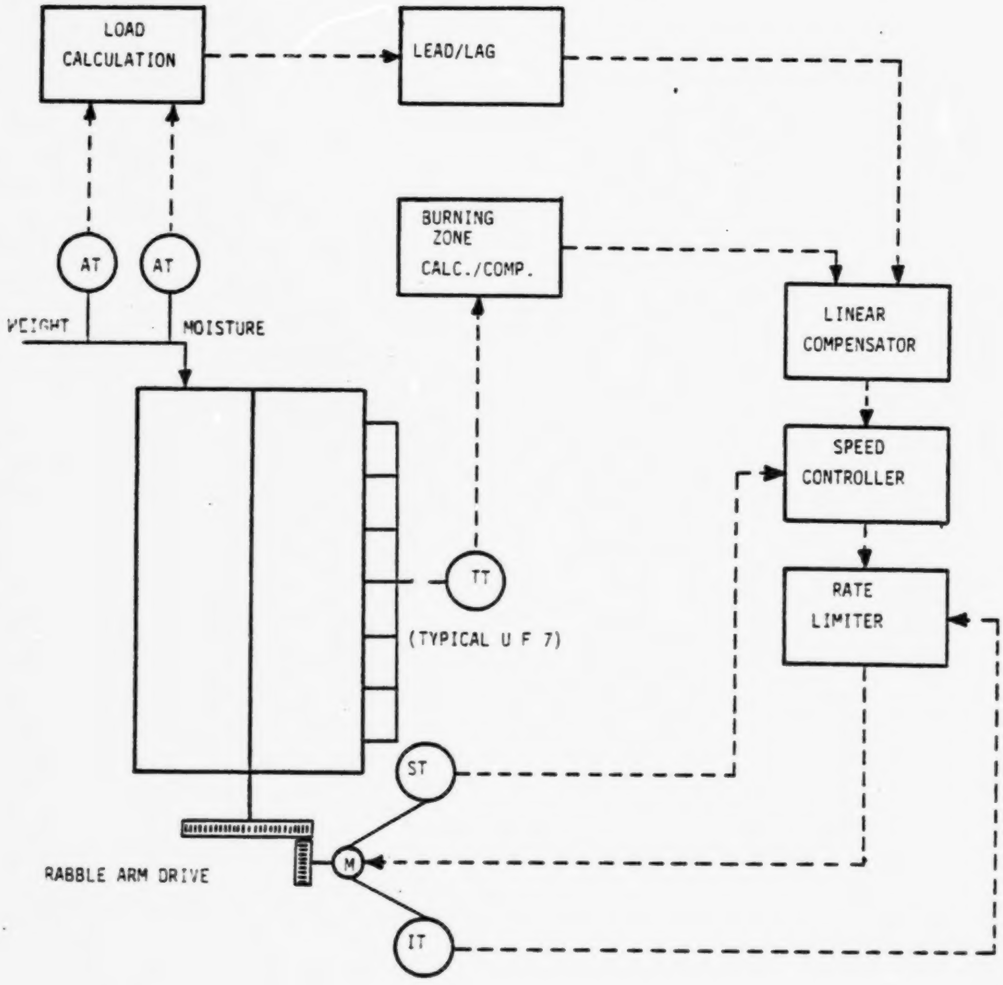


Figure 50. Schematic of rabble arm drive control.

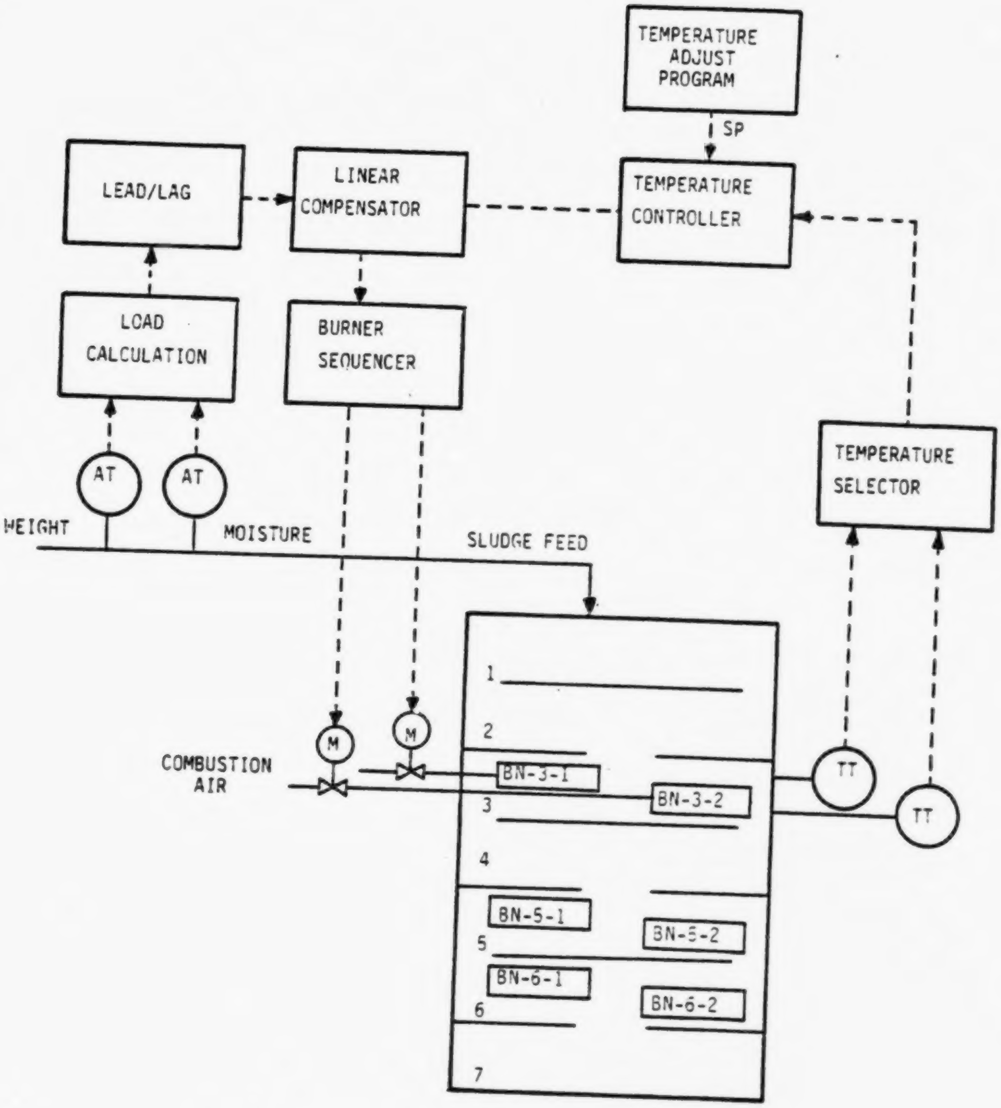


Figure 51. Schematic of temperature control for hearths 3, 5, and 6.

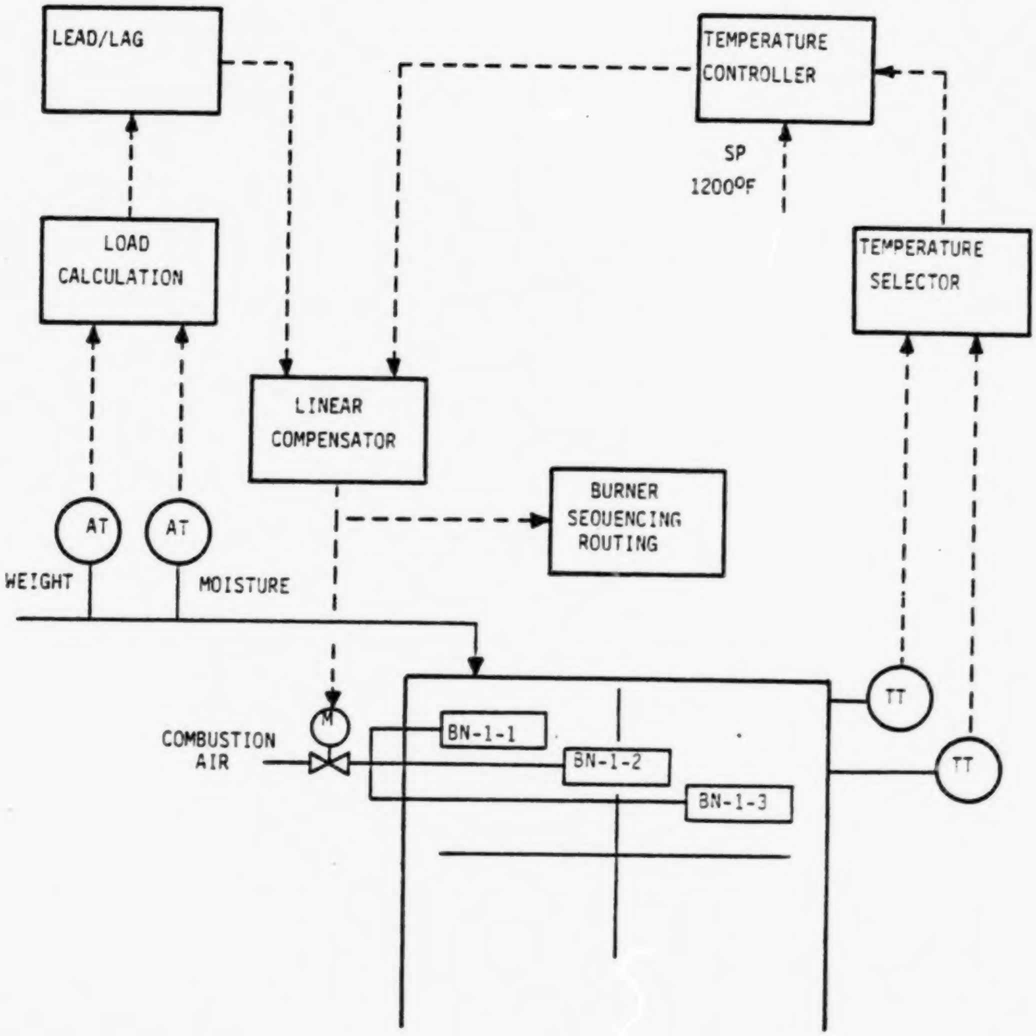
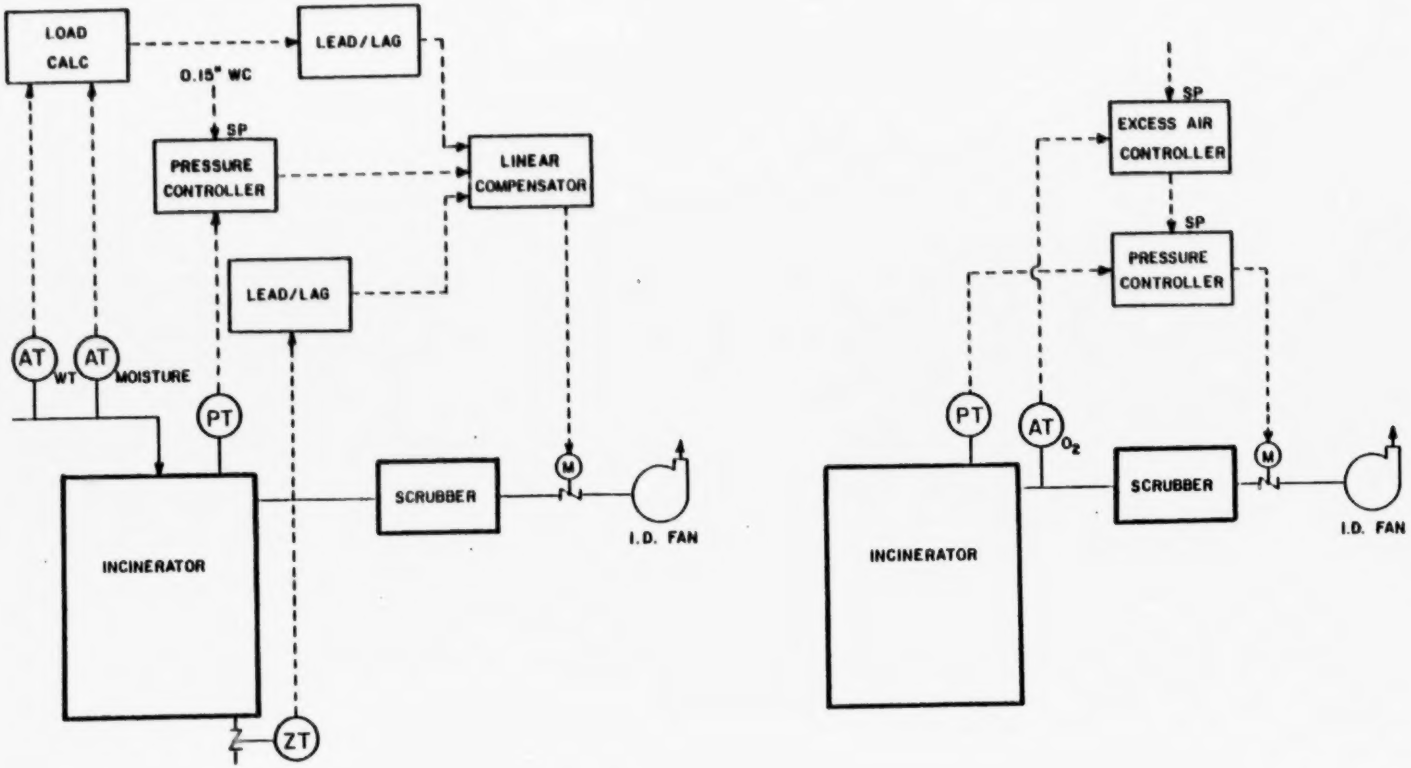


Figure 52. Schematic of hearth 1 temperature control.



– LOOP 5A –

– LOOP 5B –

Figure 53. Schematic of ID fan control.

eventually used. This consisted of the pressure controller with a manually entered setpoint. The load calculation could not be made because cake moisture data were not available; and, the interaction between the atmospheric air damper position and furnace pressure was never properly modeled because of the constraints of time and furnace availability.

Combustion Air--The air for drying, burning, and cooling is provided through an atmospheric air damper located on hearth no. 7 along with the return of the center shaft cooling air, again on hearth no. 7. The two methods of control are presented in schematic form in Figure 54. It was intended that 6A, which provided separate control for the atmospheric and shaft bypass dampers, be used with loop 5A (Figure 53). The shaft bypass damper is controlled by a PID controller with a manually entered setpoint. The damper position was used as feedback.

The atmospheric air damper is adjusted to maintain a fixed oxygen level in the stack gas; however, the incinerator load is used as a feedforward trim and the hearth temperatures are used as a second trim to detect conditions such as too much cooling air entering the incinerator.

Loop 6B assumed that loop 5B was being used to control the ID fan damper and was intended to provide temperature control of the incinerator during the periods when coal feed was operational; although, this control loop could also be used when the burner control loops were being used. The temperature control is accomplished by controlling the draft sources to the incinerator. A supervisory temperature control program monitors the temperature profile to modify setpoints to the controllers for the dampers. The shaft air damper is adjusted first; and, when the shaft air damper is full open (to the stack) then the atmospheric air damper is modulated to control temperature.

2. Monitoring

The implementation of the control loops described above required a considerable amount of instrumentation; however, with the exception of rabble arm speed, and stack gas O_2 (See Sections 6 & 14) all of the required signals were wired to the existing incinerator control panel. Since the RTU was mounted adjacent to this panel the wiring task was relatively easy; however, a considerable amount of time was required to check the calibration of all transmitters.

In addition to the on-line sensors (thermocouples, pressure transducers, position indicating devices, etc.) visual observations are required to provide additional process information. The location of the burning zone is determined by observing hearth conditions through portholes. The ash hopper must be inspected to determine if ash balls (char) are present. Ash balls cause problems in the ash transport sytem and indicate incomplete combustion. Perhaps the most important visual observation is the condition of the stack. Dark smoke indicates an upset related to insufficient combustion air, caused by low draft or overloading with cake. A provision was also made to manually enter the volatile solids content of the cake obtained from the laboratory analysis.

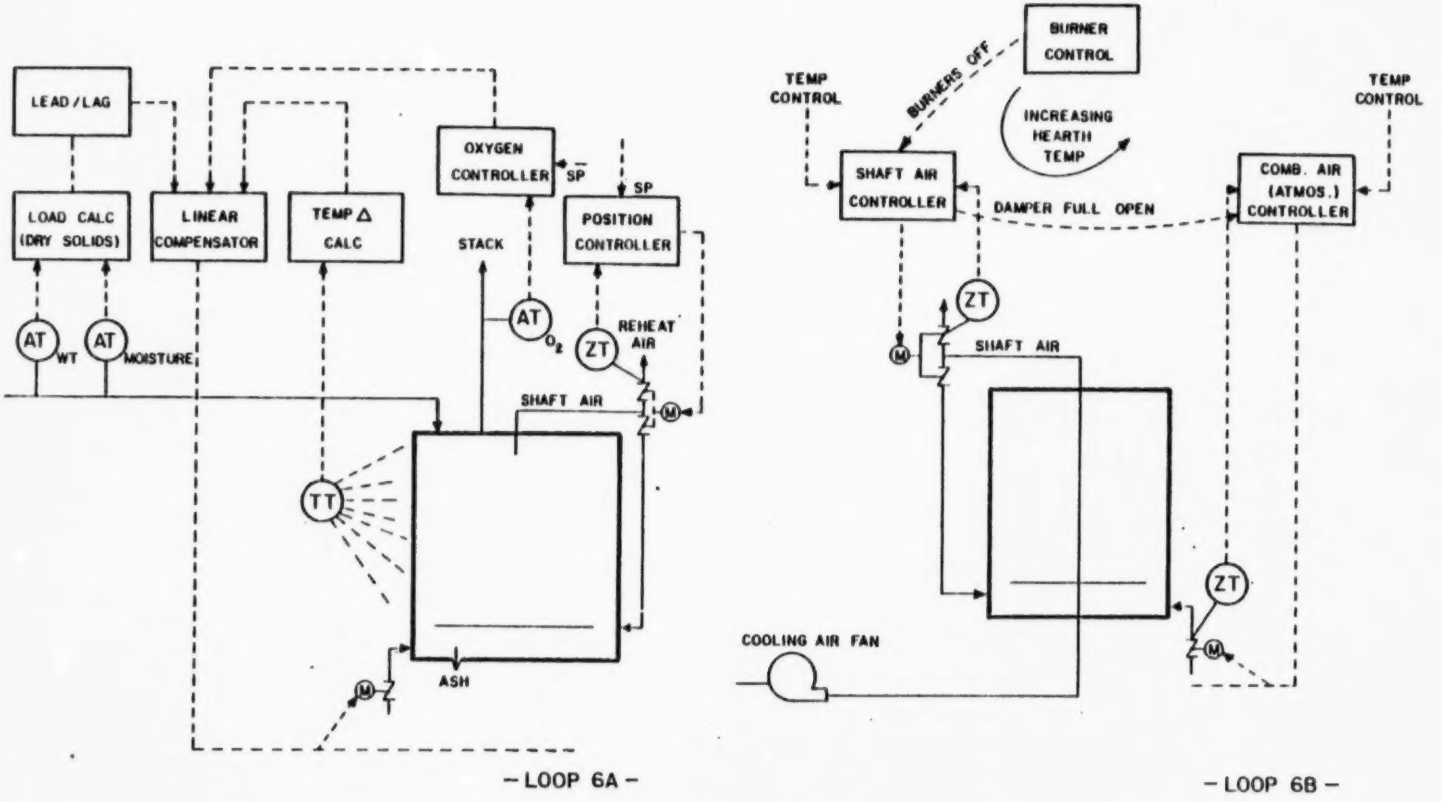


Figure 54. Schematic of combustion air control.

C. OPEN LOOP TESTS

1. Temperature

A series of open loop tests were conducted over a period of several months (delays caused by equipment downtime) to provide the characterization of process dynamics required for the proposed control schemes. The testing addressed two areas--temperature dynamics and gas flow dynamics.

In terms of temperature, the incinerator is divided into three zones--drying, burning, and cooling. At Seneca the operators historically preferred to burn on the upper hearths--using hearth no. 3 as the main burning hearth. For any given set of conditions there is an optimum temperature profile; and, the sludge feed is the main disturbance variable with respect to that temperature profile.

The solids flow through the incinerator is illustrated in Figure 55. Since cake moisture data were not available, the sludge feed could not be properly characterized and the load to the incinerator could not be calculated. The signal generated by the belt scale used to weigh cake was extremely noisy and required the use of averaging techniques to provide useful data. In addition, it was demonstrated that the response of temperature in the burning zone, to changes in wet cake loading, was slow. For this combination of reasons the cake production rate was not used as a feedforward control parameter.

Further observations demonstrated that the rabble arm speed did not effect the temperature profile in a timely manner. It is extremely difficult to evaluate loops which exhibit long deadtime because steady state conditions for other parameters are usually not obtained. In the end it was assumed that, if the cake production rate, moisture, and volatile content were maintained in reasonable ranges, the combustion controls of the burners would react to deviation from the desired temperatue profile.

During the open loop testing it was observed that the thermocouple on hearth no. 6 responded rapidly to increased fuel flow to burners on hearth no. 5. After some investigation it was deduced that heat was transferred by radiation through a drop hole. Several months after this observation incinerator no. 1 was taken out of service for required maintenance. During this period the drop hole was covered with a steel plate, which in turn, was covered with several inches of ash. When the furnace was put back into service the interaction between hearths no. 5 and no. 6 was no longer observed.

2. Air

The incineration process requires air in a sufficient quantity to assure combustion of the fuel and volatile solids charged to the furnace. In practice this quantity is considerably higher then the stoichiometric requirement. When incinerating sludge it is not uncommon to provide two times the stoichiometric amount or 100% excess air. In an emergency, air can be used to cool the incinerator to prevent damage which may be caused by excessive temperature. Such operation, however, wastes considerable energy in the form of heat.

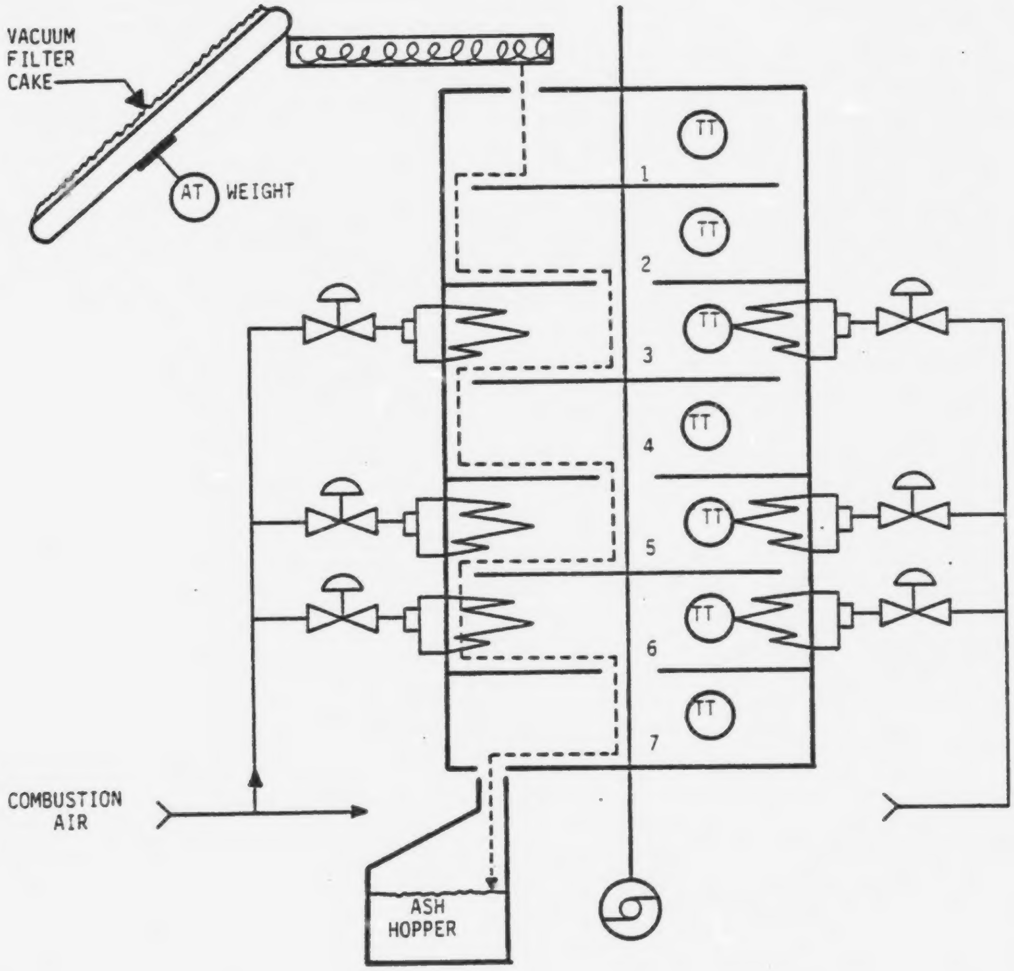


Figure 55. Sludge flow through incinerator.

The general air flow schematic for the Seneca incinerators is illustrated in Figure 56. The major design sources of air are the atmospheric air entrance on hearth no. 7, the return of shaft cooling air, also on hearth no. 7, and the combustion air entering at the burners. Unknown quantities of air can enter on hearth no. 1 with the cake and at any portholes left open after inspection.

One of the first open loop tests demonstrated that the oxygen content of the flue gas was independent of the position of the atmospheric air damper. It was, however, observed that by recycling approximately 50% of the shaft cooling air the flue gas oxygen content was increased by approximately 1.5% O_2. The capacity of the cooling air fan is 150 sm^3/min (5300 scfm). These tests were conducted with the draft (hearth no. 1 negative pressure) in the range of 0.4 to 1.3 cm (0.15 to 0.5 in) of water.

The above tests indicated that control of the excess air rate, by means of O_2 control, was not promising. Subsequent investigations, however, demonstrated that significant quantities of air entered through two openings on the bottom of the furnace. The door to the ash slurry tank had been removed for the sake of convenience because the operators must inspect the slurry tank at frequent intervals. A new door was fabricated to allow more convenient access.

As the ash discharges from hearth no. 7 it falls through an inclined bar rack before entering the quench tank. The purpose of the bar rack is to remove ash balls and other large debris which would cause problems in the ash transfer system. The bar rack must be raked periodically; and, it is thus not possible to entirely seal hearth no. 7 from uncontrolled air sources.

Subsequent tests, conducted in August, 1980, demonstrated that, with the furnace draft set at 0.4 cm (0.15 in) H_2O, opening the ash door increased the oxygen content of the flue gas by approximately 1 to 1.5% O_2 (9% to 10.5%). It was also observed that the status of the burners effected both the furnace draft and the measured oxygen content. As the burners went to full fire position the draft decreased from 0.4 cm (0.15 in) to about 0.25 cm (0.10 in); and, the flue gas oxygen increased from about 8% to 9%.

In addition to the above interaction it was observed that as the cooling air damper opened, forcing more shaft cooling air into hearth no. 7, the furnace draft measurably decreased. For example, as the damper was opened from 30% open to 40% open, the furnace draft fell from 0.4cm (.15 in) to 0.2 cm (0.08 in). In fact this test was aborted because the ID fan did not have the capacity to produce the required draft. Depending on operating conditions smoke can be discharged to the building at draft values below about 0.13 cm (0.05 in).

The results of the open loop tests demonstrated significant interaction between the parameters tested. Because of this interaction the possibility of providing a control scheme which responded rapidly to maintain excess O_2 in a narrow range was not considered feasible. It was felt, however, less than optimum control would still offer improvements when compared to the existing system of manual/analog control.

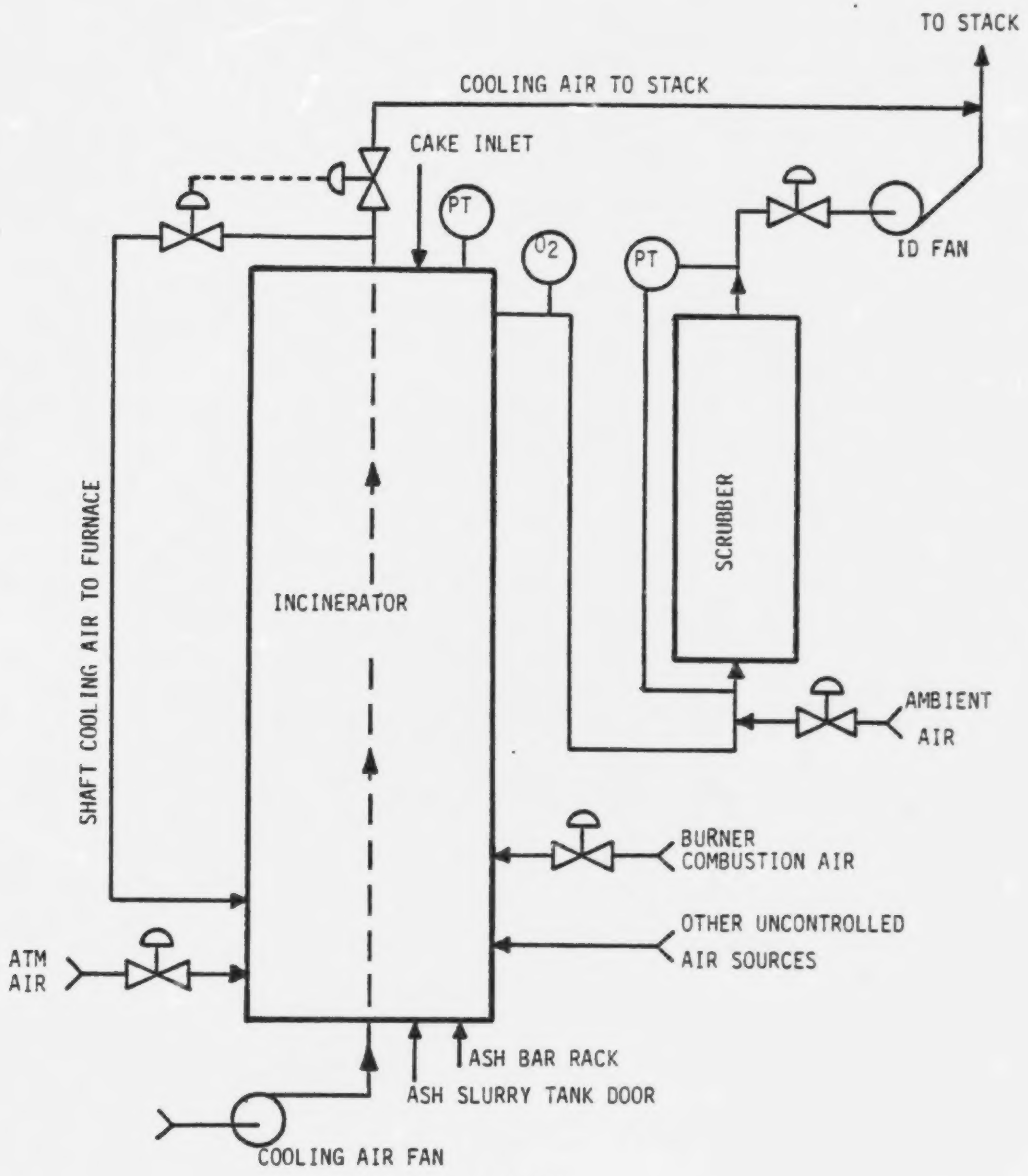


Figure 56. Air flow through incinerator.

D. STACK EMISSIONS

At about the same time the open loop tests were completed, the MWCC Operations Department initiated a study to determine if the Seneca incinerators could be operated at, or near, rated capacity and still meet the applicable air quality emission standard of 0.10 grains particulate per dry standard cubic foot corrected to 12% CO_2 (net). The second goal of the study was to identify the most fuel efficient operating mode.

The results of this study demonstrated that the scrubber efficiency was increased by reducing the gas flow and increasing the water flow. It was recommended that the scrubber ambient air damper, Figure 55, be sealed shut and that sufficient water be used in the scrubbing system to cool the exit gas to 27°C (80°F). This would require a water flow of approximately 1700 l/m (450 gpm); and, would yield a pressure drop of approximately 17 cm (6.5 in) H_2O across the scrubber.

The results of this study demonstrated that in order to maximize fuel efficiency three distinct zones should be maintained in the furnace as follows: (a) cake drying should be conducted on hearths 1, 2, and 3, (b) complete combustion should be obtained on hearths 4 and 5, and (c) the ash should be cooled on hearths 6 and 7. It was further determined that the above zones could be maintained when the following operating mode was used.

Furnace draft	0.4 cm (0.15) H_2O
Shaft cooling air	100% return to hearth no. 7
Ambient air	0-20% open as required
Hearth 6 burner	Off
Hearth 5 burner	100% capacity
Hearth 3 burner	Control to 650°C (1200°F)

When this operating mode was used it was demonstrated that the temperature profile presented in TABLE 22 could be maintained. By eliminating burning on the upper hearths, the thermal efficiency was increased; and, it was determined that overall thermal efficiencies of approximately 4420 kJ/kg (1900 BTU/lb) water evaporated could be obtained. Typical reported values fall in the range of 4200 kJ/kg (1800 BTU/lb) to 5800 kJ/kg (2500 BTU/lb). (22) Using totals for the five-year period 1976 through 1980 the thermal efficiencies at Seneca averaged approximately 5470 kJ/kg (2350 BTU/lb) H_2O.

E. PROPOSED CONTROL STRATEGY

The control strategy was organized into two areas, temperature and gas flow. The temperature control scheme was designed to maintain the temperature profile presented in TABLE 22. Because it was previously demonstrated that the desired temperature could be maintained without heat input on hearth no. 6, only the burners on hearths no. 3 and 5 were used regularly. The burners on hearth 6 were, however, controlled from a manually operated setpoint.

TABLE 22. RECOMMENDED TEMPERATURE PROFILE

Hearth No.	Temperature - °C (°F)		
	Minimum	Average	Maximum
1	400 (750)	430 (800)	450 (850)
2	450 (850)	480 (900)	540 (1000)
3	650 (1200)	700 (1300)	760 (1400)
4	760 (1400)	870 (1600)	980 (1800)
5	590 (1100)	650 (1200)	700 (1300)
6	200 (400)	260 (500)	310 (600)
7	80 (180)	90 (200)	90 (200)

The burner control loops for hearths no. 3 and 5 are illustrated in Figure 57. The hearth 3 burner control was designed to maintain a temperature on hearth 2 that was high enough to promote proper drying of the sludge cake, yet low enough to avoid excessive heat losses in the exhaust gases. To maximize utilization of energy from auxiliary fuel, the hearth 5 burners were normally operated at maximum capacity. If, however, the hearth 4 and 5 temperatures were above the specified ranges and the hearth 3 burner was positioned to 0%, the temperature profile controller would decrease the hearth 5 burner position controller's setpoint. This insured that the energy value of the cake would be used before auxiliary fuel was used.

The control of gas flow through the furnace was divided into two areas, draft and oxygen control. Since the draft (negative furnace pressure measured on hearth no. 1) reacts rapidly to changes in gas flow, the scan rate for this loop was relatively rapid--30 seconds. The draft setpoint was manually entered and the controller output adjusted the position of the ID fan damper, Figure 56, to maintain that value.

The gas flow through the furnace was controlled to maintain a manually entered setpoint for the flue gas oxygen content (excess air)--see Figure 58. The measured oxygen value was used as feedback. The results of the furnace testing indicated that all of the shaft cooling air should be returned to the furnace before the atmospheric air damper was opened. This was accomplished by utilizing two independent controllers and setpoints as illustrated. Subsequent tests demonstrated that in many cases sufficient oxygen could be obtained without opening the atmospheric air damper.

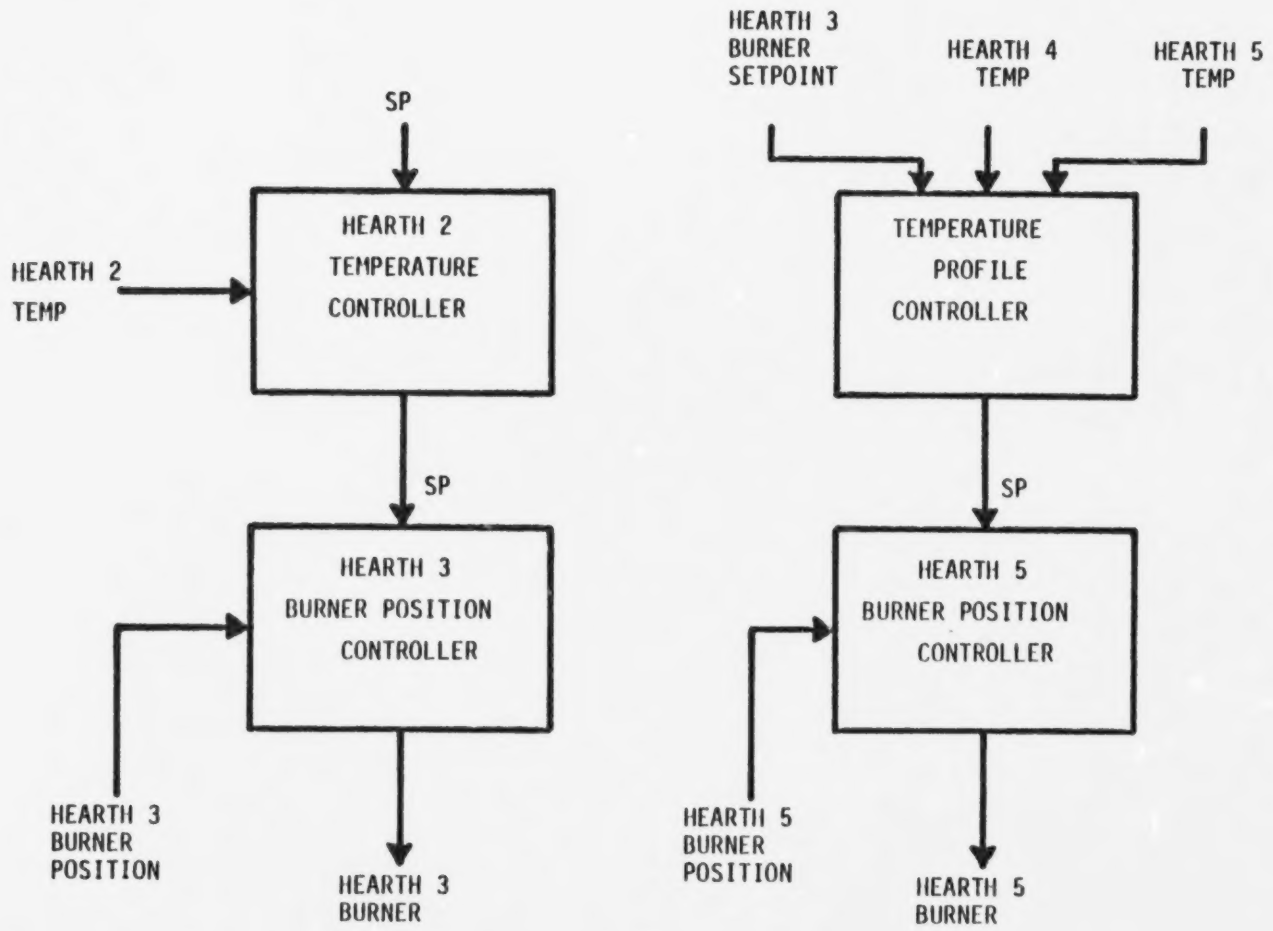


Figure 57. Schematic of burner controls for hearths 3 and 5.

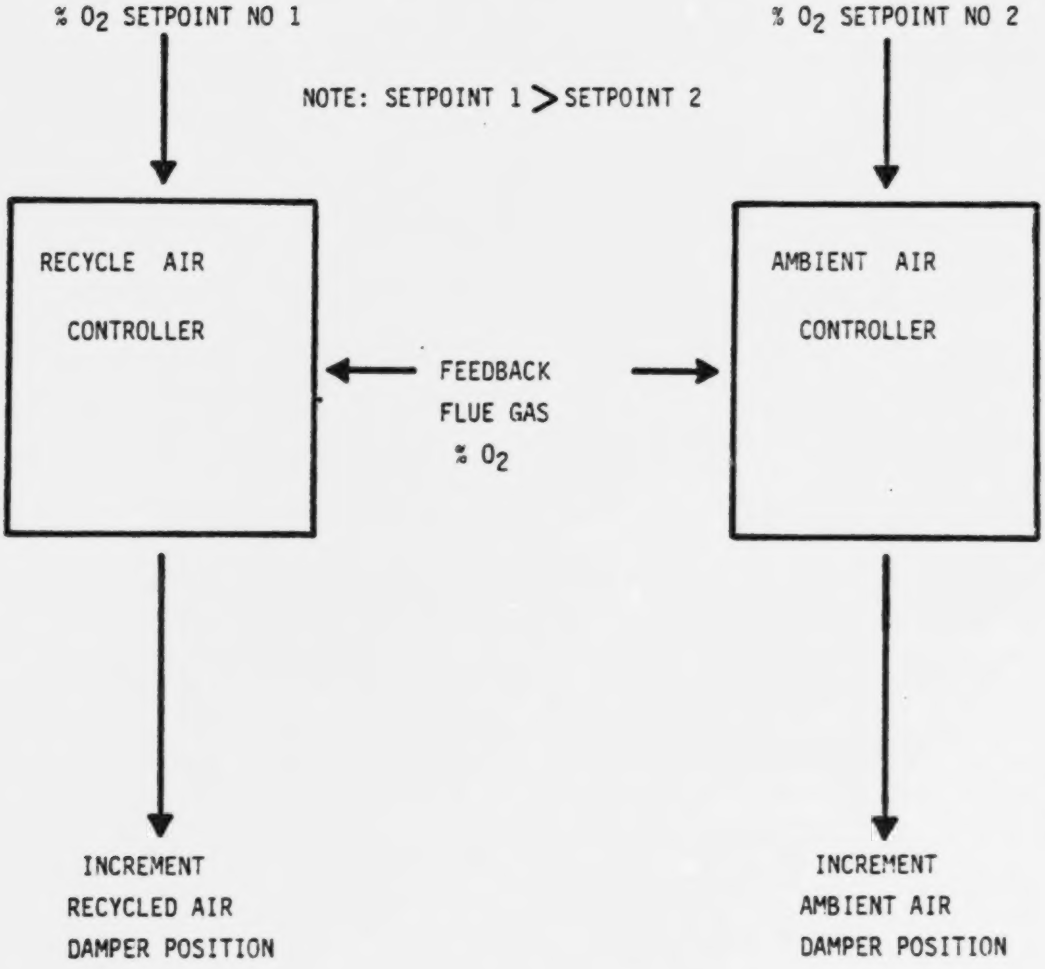

% O2 SETPOINT NO 1
% O2 SETPOINT NO 2
NOTE: SETPOINT 1 > SETPOINT 2
RECYCLE AIR CONTROLLER
AMBIENT AIR CONTROLLER
FEEDBACK FLUE GAS % O2
INCREMENT RECYCLED AIR DAMPER POSITION
INCREMENT AMBIENT AIR DAMPER POSITION

Figure 58. Schematic for incinerator excess air control.

SECTION 14

EVALUATION OF AUTOMATED SOLIDS PROCESSING

A. GENERAL

During the project planning stages, the final evaluation, or demonstration, of automated solids processing at Seneca was envisioned as a long period (> 10 days) during which both process trains would be operating, one automated (no. 1) and the other (no. 2) manually controlled. During the initial evaluations of the control hardware for the vacuum filter it became obvious that the probability of having both process trains operate simultaneously for an extended period, along with the required control hardware, was very low. Scheduled maintenance usually required the shutdown of one train; and, unscheduled maintenance related to the vacuum pumps and ash transport system often caused the shut down of both process trains. If the shutdown was prolonged, the sludge inventory would increase; and, the operators were reluctant to give up control of the process until the inventory was reduced.

The incinerator control software was completed early in June, 1981. At that time both sludge processing trains were operating; however, the performance of the vacuum pumps was marginal. If the vacuum pumps were taken out of service for repair it was anticipated that the opportunity for a parallel test might not occur for several months. Because of this situation, the evaluation was started before the control software was field tested. Two tests were conducted during June, 1981. Early in July, 1981 the disc drive on the computer failed and the control system was out of service for a prolonged period. All field work was thus terminated after the second test in June.

B. CHRONOLOGY

1. Test No. 1

The initial comparison of automated and manual control for the two process trains was conducted during the period June 9-12, 1981. The initial setpoints for process train no. 1 were as follows:

Parameter	Setpoint
Wet cake yield	5.4 mt/hr (6TPH)
pH of $FeCl_3$ conditioned sludge	5.4
pH of lime conditioned sludge	12.0
Incinerator draft	5mm (0.2 in) H_2O
Flue gas O_2	6%

Hearth #2 temperature	565°C (1050°F)
Hearth #5 temperature	850°C (1500°F)

The atmospheric air damper was operated manually throughout the test because of a malfunction in the computer/damper interface module; however, it was usually closed throughout the test. The burners on hearth no. 3 were controlled to maintain the hearth no. 2 setpoint temperature. The burners on hearth no. 5, however, were normally operated at the full open position. These burners were throttled only when the hearth no. 5 temperature exceeded the setpoint value.

Unstable vacuum pump operation plagued both operating trains throughout the test period causing interruptions in filter and incinerator control. An abnormally wet cake and problems with the draft control caused an overload condition and a four hour interruption in the controlled incinerator operation three hours into the test run. Computer control was resumed after the burning zone was reestablished on hearth 4. A concurrent reduction in the filter cake production rate aided the recovery. Computer control continued until 10 A.M. on June 10 when both operating trains were shut down several hours for sludge pump maintenance. During the interruption a control limit was established for the induced draft damper in order to prevent the large changes in draft observed during the control run.

Automated filter and incinerator operation was resumed at 1 P.M. on June 10. The recycled air oxygen setpoint was increased to 8.4% in an effort to reduce smoke generation. Adjustments in the atmospheric air damper position did not reduce the amount of smoke generated based on stack observations. Inconsistent filter vacuum continued to affect cake quality. The filter cake production setpoint was lowered to 5 mt/hr (5.5 TPH) until 7 P.M. to reduce the water loading on the incinerator. Controlled filter and incinerator operation continued until 8 A.M. on June 11 when both filters were shut down for vacuum pump maintenance. Intermittent incinerator operation difficulties were encountered from 7 P.M. - 8 A.M. (June 10 - 11) resulting in occasional low draft and correspondingly low oxygen concentrations. Atmospheric air was added manually to increase the oxygen concentration. One of the hearth 3 burners malfunctioned at 6 A.M. necessitating a manual restart. Both hearth 3 burners were returned to computer control at 6:30 A.M. The burner failure caused a sharp drop in the burning zone temperature.

Vacuum filter and incinerator control was resumed at 6 P.M. on June 11. Incinerator control was returned to manual mode at 8:30 P.M. due to overloading following an increase in the cake production setpoint to 5.9 mt/hr (6.5 TPH). At 9 P.M. the filter drum was temporarily placed in manual control due to loss of vacuum. The incinerator was returned to computer control at 10:30 P.M. after the burning zone was reestablished on hearth 4.

High temperatures were observed on hearth 4 from 3 to 9 A.M., June 12 because of excess heating from the hearth 5 burners. The burner firing rate was reduced manually on two occasions in order to lower the burning zone temperature. The recycled air damper was closed manually several times to increase the draft and reduce smoke generation. The control run was terminated at 10 A.M. on June 12 for vacuum pump inspection and maintenance.

2. Test No. 2

This test was conducted during an 11-hour period (11 A.M. - 10 P.M.) on June 24, 1981. The initial setpoints for process train no. 1 were as follows:

Parameter	Setpoint
Wet cake yield	5.4 mt/hr (6TPH)
$FeCl_3$ dose	11% of dry sludge solids
pH of lime conditioned sludge	12.0
Incinerator draft	5mm (0.2 in) H_2O
Flue gas O_2	7.4%
Hearth #2 temperature	565°C (1050°F)
Hearth #4 temperature	980°C (1800°F)

The major modifications for the second test were: to base $FeCl_3$ feed on dose rather than pH, to increase the flue gas O_2 setpoint, and to base the operation of the burners on hearth no. 5 on the hearth no. 4 temperature.

A significant amount of smoke was observed approximately 90 minutes into the run. The recycled air oxygen setpoint was increased to 9.4% in an effort to reduce the smoke emissions. Unstable filter vacuum caused several upsets in filter control during the run. At 3:20 P.M. the cake production setpoint was reduced to 5 mt/hr (5.5 TPH) in order to achieve a more stable operation. At 4:10 P.M. the maximum temperature setpoint (hearth 4) for hearth 5 burner control was reduced to 953°C (1750°F) and the recycled air control setpoint was increased to 10.5% oxygen. At 7:35 P.M. the computer was brought on-line following a lockup. At 8:30 P.M. one of the burners on hearth 3 failed. The burner was restarted and returned to operation at 9 P.M. At 9:20 P.M. low draft combined with low oxygen concentrations caused a temporary increase in smoke generation. The incinerator recovered from the adverse conditions in approximately 20 minutes after increases in draft and oxygen concentration were observed. No adjustments were made in incinerator control setpoints during the upset. At 9:10 P.M. the ferric chloride dose setpoint was reduced to 10%. Control run monitoring was terminated at 10 P.M. with both the filter and incinerator operating normally.

C. TEST RESULTS

1. Test No. 1.

a. Dewatering

The performance data for the two dewatering trains are summarized in TABLE 23. Because of the problems encountered with the vacuum system, automated control of vacuum filter no. 1 was maintained for only 37 hours of the 51 total operating hours. Periodically the form vacuum would be so small that cake would not form on all sections of the media. When such a section reached the drying zone the dry vacuum would decrease dramatically. This would require that the filter be shut down and restarted in the manual mode. The restart procedure consisted of lowering the drum speed, increasing the vat level and turning the form vacuum on. When cake covered the drum the dry vacuum was turned on and the drum speed and vat level adjusted to setpoint. The cake discharged during a startup period is extremely wet.

TABLE 23. DEWATERING PERFORMANCE DURING TESTS NO. 1

Parameter	Filter No. 1		Filter No. 2
	Computer	Total	
Hours	37	51	45
Sludge flow - l/sec (gpm)	4 (64)	-	3.1 (50)
Raw sludge solids - %	4.4	4.4	4.4
$FeCl_3$ - %	13	-	14
CaO - %	19	-	24
Yield - wet mt/hr (TPH)	5 (5.5)	5 (5.5)	4 (4.4)
Cake Solids - %	18.7	18.6	19.2
Cake Volatile Solids - %	55.5	53.7	49.2
Cake - lb H_2O/lb Volatile	7.8	8.2	8.6

Throughout the test train no. 1 processed more sludge and produced a cake with a slightly lower solids content but significantly higher volatile content. The increased volatile content was a direct result of lower concentrations of conditioning chemicals, primarily lime.

The wet yield and drying zone vacuum for both trains are summarized in Figure 59 as hourly averages. The impact of the vacuum problem is not completely evident using this method of presentation. During most of the test, instantaneous values for both the vacuum and wet yield were printed at approximately two-minute intervals on the trend report. The following summary for the one-hour period, 0500-0600 June 10, illustrates the variable loading to incinerator No. 1, although not necessarily representative variability.

	Vacuum-in Hg	Wet Yield-tph
Ave. for hour (15 sec. values)	6.0	6.1
Ave. for 28 trend values	5.7	5.9
Std. dev. for 28 trend values	3.8	2.0
Min. for 28 trend values	1.7	2.0
Max. for 28 trend values	11.1	10.1

Although the parameters for vacuum filter No. 2 were not printed on the trend report it is assumed that the variability of the vacuum and yield were similar.

b. Incineration

The efficiencies of the two process trains in terms of fuel use are summarized in TABLE 24. Incinerator no. 1 was under computer control for 41 of the 51 operating hours. Although incinerator no. 1 consumed more natural gas per hour, the higher loading rate along with the higher volatile content resulted in less fuel use per wet ton of cake and per lb of water.

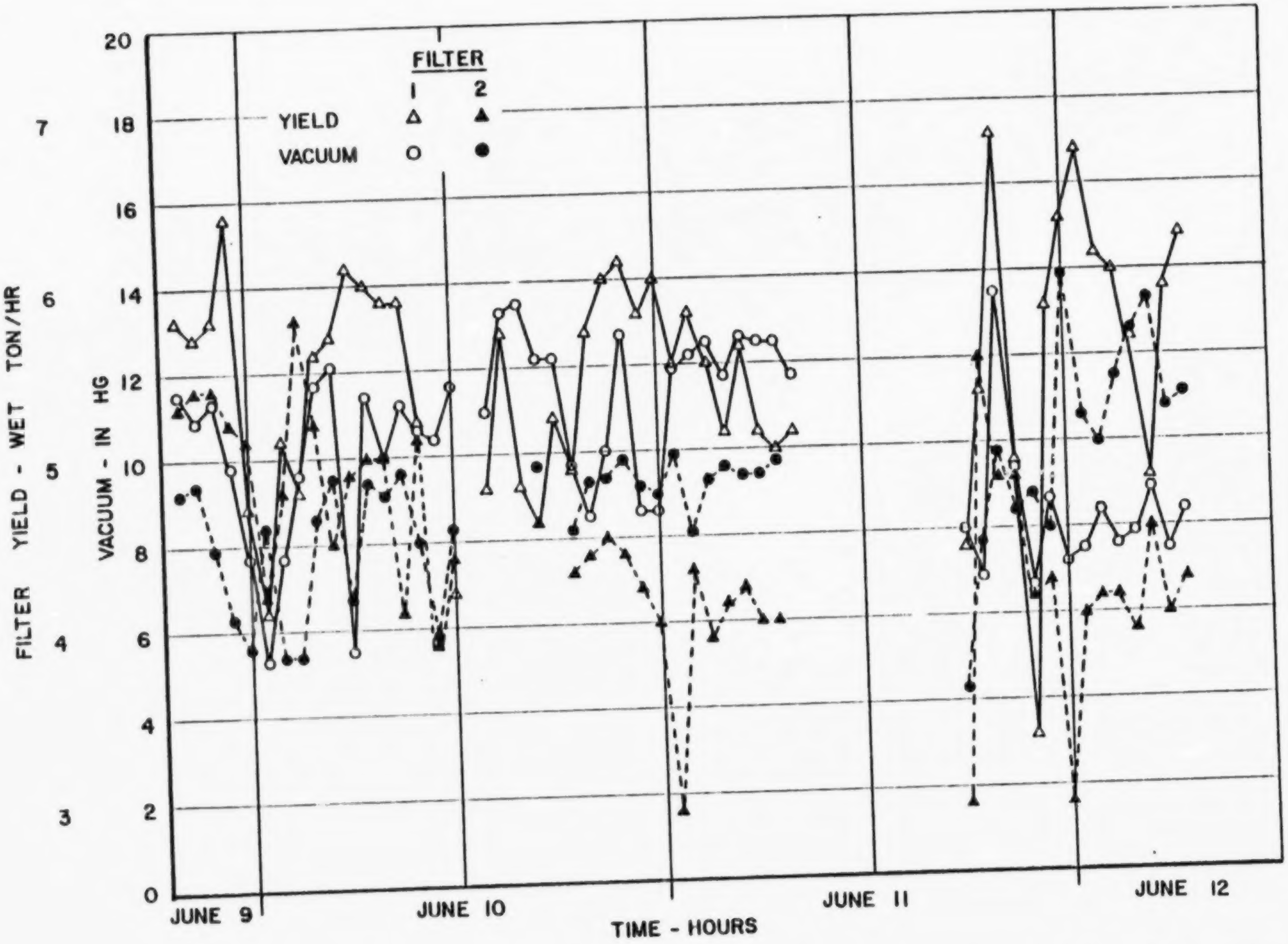


Figure 59. Filter yield and dry vacuum for filters no 1 and no 2 for test of June 9-12, 1981.

TABLE 24. INCINERATOR PERFORMANCE DURING TEST NO. 1

Parameter	No. 1 (Computer)	No. 2 (Manual)
Hours	41	45
Gas use - sm^3/hr (SCFH)	283 (10,000)	252 (8,900)
Gas use - sm^3/wet mt (SCF/wet ton)	56 (1,800)	62 (2,000)
Gas use - sm^3/dry mt (SCF/dry ton)	312 (10,000)	328 (10,500)
Total energy - kJ/kg H_2O (BTU/lb H_2O)	5,350 (2,300)	5,465 (2,350)
Gas - kJ/kg H_2O (BTU/lb H_2O)	2,560 (1,100)	2,910 (1,250)

The hourly average temperatures for both incinerators are summarized in Figure 60. For furnace no. 2 the burning zone was maintained on hearth no. 3 throughout the test. This was common practice at that time. In furnace no. 1 the burning zone fluctuated between hearths 3, 4. and 5 with no. 4 being the primary burning hearth. The automated control strategy utilized the burners on hearth no. 5 as the primary heat source which allowed the burning zone to be lowered somewhat.

Since a maximum temperature strategy was not employed, the temperature on hearth No. 4 approached 980°C (1800°F) on several occasions. In furnace no. 2 however, the maximum temperature on the burning hearth did not exceed 870C (1600F). Exit gas temperatures for furnace no. 1 were usually 28C to 38C (50F to 100F) lower than for furnace no. 2 indicating less heat wasted to the stack.

Recycled air and draft control data for furnace no. 1 are presented in Figure 61. The exit gas oxygen concentration used to control recycled air shows substantial deviations from the setpoint value on June 9 and 12. The large deviation in oxygen concentration can be attributed to the excessive draft observed during the same periods. Although a constant draft setpoint of 5mm (0.2 in) was employed throughout the run, on several occasions negative pressures in excess of the setpoint were observed creating high air flow rates and increased oxygen concentrations. Periods of excessive draft could not be prevented under the control strategy employed because of a control limit implemented on the induced draft damper. The limit prevented the damper from closing too far thus avoiding large positive changes in furnace pressure which could have led to shut down of all burners.

When the furnace pressure increased beyond the setpoint value of -0.20 in. the oxygen content of the exit gas would decrease. It was observed that when the recycle air damper would open completely the furnace pressure would increase; and the induced draft fan did not have sufficient capacity to return the pressure to setpoint. Under these conditions, the measured oxygen concentration in the exit gas decreased and smoke was observed on the burning hearths. The situation was not rectified until the recycled air damper was manually closed.

Based on observations conducted during the test, the recycled air oxygen setpoint employed initially (7.0%) was not sufficient to prevent smoke generation. Increased oxygen setpoints employed during the latter stages of the test

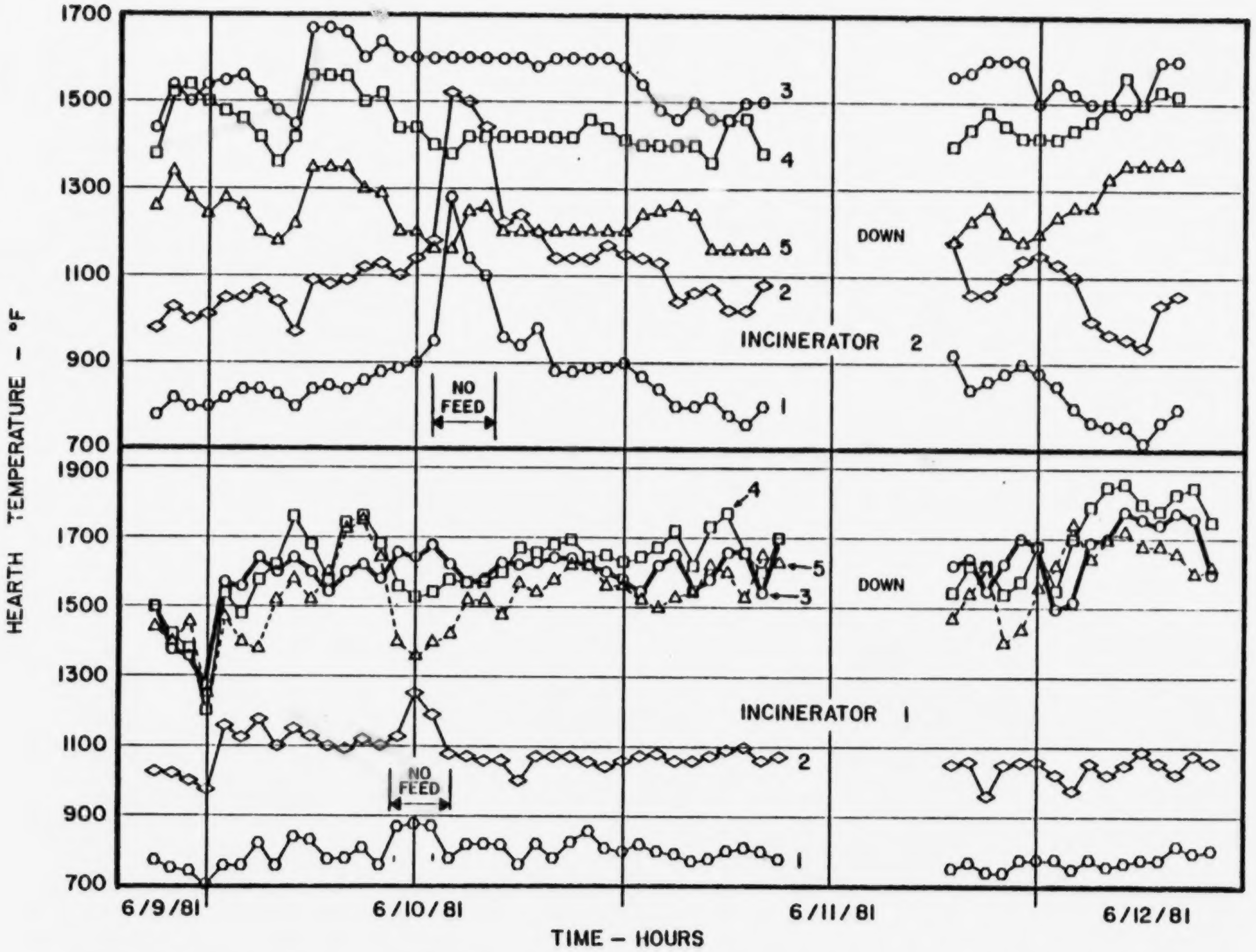


Figure 60. Temperature profiles for incinerators no 1 and 2 for test of June 9-12, 1981.

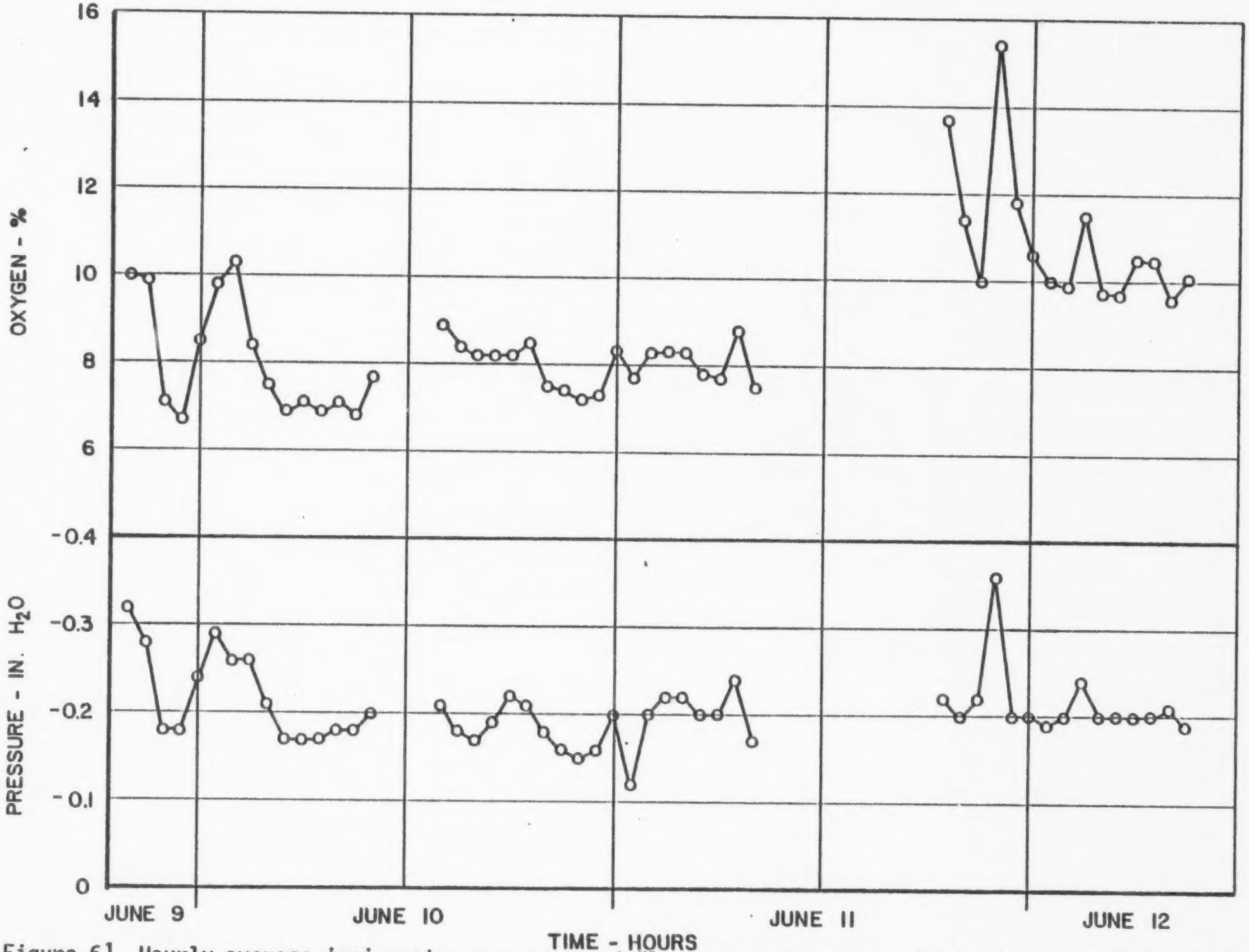


Figure 61. Hourly average incinerator pressure and flue gas oxygen conc. for test of June 9-12, 1981.

noticeably improved the stack quality; however, these setpoints were significantly higher than predicted based on operation at 100% excess air. The high oxygen setpoint requirements may have been caused by air entry through the filter cake inlet drop gate which produced erroneously high oxygen readings, or by short-circuiting of air in the incinerator causing insufficient mixing for controlled burning.

2. Test No. 2.

a. Dewatering

The performance data for the two dewatering trains are summarized in TABLE 25. As in the previous test the vacuum system limited the performance of both trains. During the 9th hour of the test both filters lost vacuum, were shut down, and restarted manually.

TABLE 25. DEWATERING PERFORMANCE DURING TEST NO. 2

Parameter	No. 1 (Computer)	No. 2 (Manual)
Hours	11	11
Sludge flow - l/sec (gpm)	4.4 (70)	4.2 (66)
Raw Sludge solids - %	4.1	4.1
$FeCl_3$ - %	11	8.5
CaO - %	18	25
Yield - wet mt/hr (TPH)	4.7 (5.2)	4.4 (4.9)
Cake Solids - %	20.6	21.2
Cake Volatile Solids - %	53.8	44.1

Filter no. 1 again produced a cake with a significantly higher volatile solids content. This was again primarily due to the reduced lime dose used in train no. 1. The $FeCl_3$ dose in train 2 was lower than normal because the actual discharge capacity of the chemical feed pump was only 45% of its nominal capacity.

b. Incineration

The fuel efficiencies of the two process trains are summarized in TABLE 26. The performance of both trains improved significantly in terms of total energy consumed per mass of water fed. Because of the higher volatile content however, furnace no. 1 was more efficient in this respect.

As illustrated in Figure 62 the operators maintained a temperature profile in Furnace no. 2 somewhat similar to that of the first test; i.e., burning on hearth no. 3. The average temperature on hearth no. 5, however, increased approximately 83°C (150°F). This increased temperature and the increase in the overall efficiency were most likely caused by a decrease in the air flow through furnace no. 2. During this second test the operators maintained the furnace pressure at about -0.38 cm (-0.15in); whereas, during the

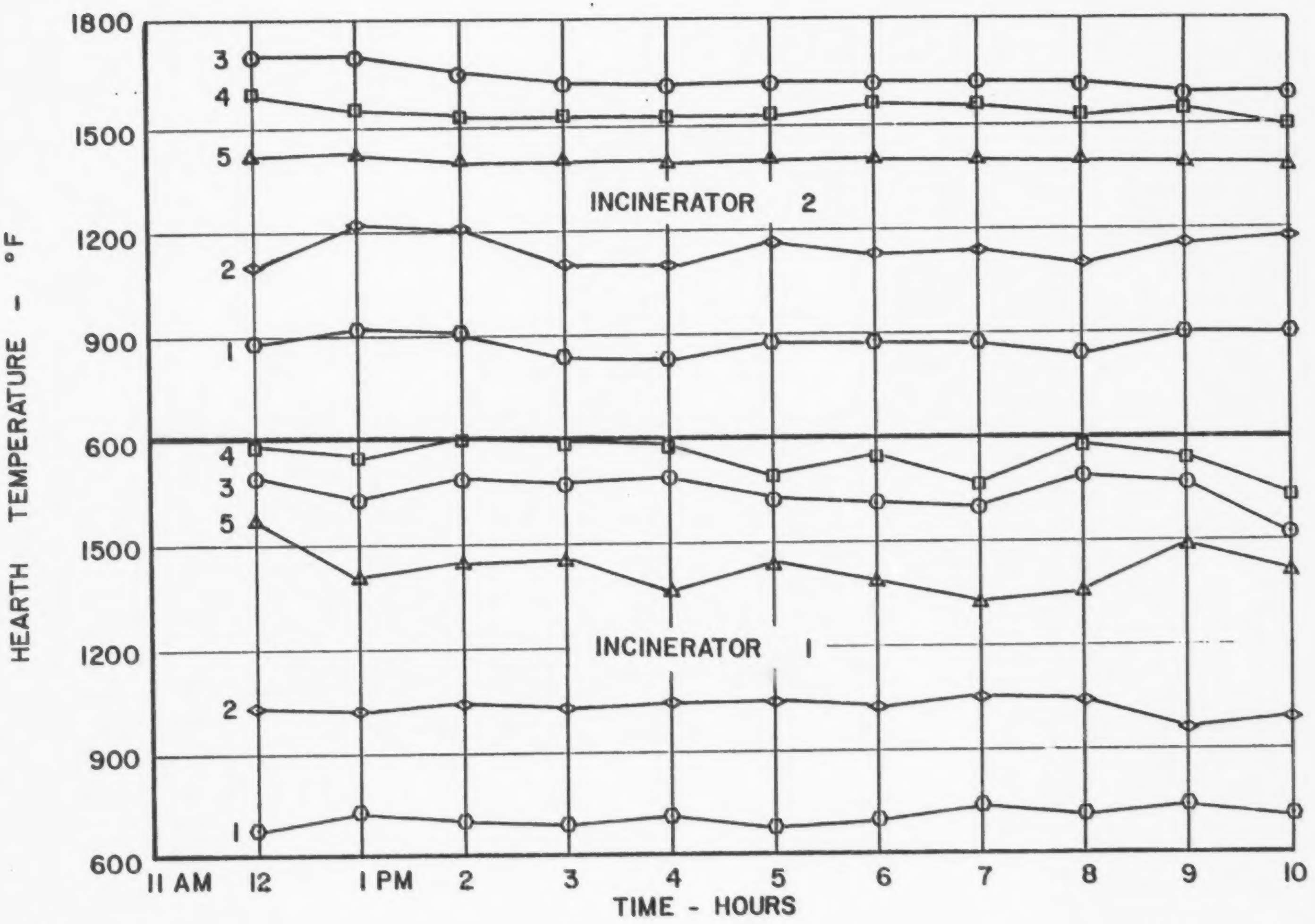


Figure 62. Temperature profiles for incinerators no 1 and no 2 for test on June 24, 1981.

first test the pressure averaged -0.50 cm (-0.2 in). Thus, although the exit gas temperature was slightly greater during this second test, the reduced air flow rate most likely limited heat loss to the stack.

TABLE 26. INCINERATOR PERFORMANCE DURING TEST NO. 2

Parameter	No. 1 (Computer)	No. 2 (Manual)
Hours	11	11
Gas use - sm^3/hr (SCFH)	184 (6,500)	218 (7,700)
Gas use - sm^3/wet mt (SCF/wet ton)	39 (1,250)	50 (1,600)
Gas use - sm^3/dry mt (SCF/dry ton)	184 (5,900)	240 (7,700)
Total energy kJ/kg H_2O (BTU/lb H_2O)	4,885 (2,100)	4,885 (2,100)
Gas - kJ/kg H_2O (BTU/lb H_2O)	1,860 (800)	2,325 (1,000)

The improvement in the efficiency of furnace no. 1 can be attributed to the implementation of an upper temperature limit for hearth no. 4 (initially 980°C 1800°F changed to 1750°C at 1610 hrs) which throttled the burners on hearth no. 5. The exit gas temperature during this test was approximately 42°C (75°F) cooler than during the previous test. This confirms the advantage of burning lower in the incinerator.

The furnace pressure and oxygen data are summarized in Figure 63. A draft setpoint of 5 mm (0.2 in) was employed throughout the control run. Several excursions from the pressure setpoint are evident. A corresponding change in the oxygen concentration resulting from the pressure excursions is also evident. The pressure excursions appeared to be caused by the recycle air damper swinging to the fully open or closed position which caused significant changes in air flow. Low draft values resulted in significant smoke production which was identified through both hearth and stack observations. Increases in the oxygen setpoint improved the stack quality during the test.

D. DISCUSSION

The results of the two tests demonstrate that automated control of the solids processing trains at Seneca can yield a substantial savings. The annual savings associated with reduced use of conditioning chemicals, discussed in Section 11, are estimated to be approximately $50,000 when historical chemical use is considered. The annual savings associated with reduced energy consumption are estimated below.

For the three-year period 1978-1980 the auxiliary energy required for incineration averaged 12.7 x 10^6 kJ/mt (13.24 x 10^6 BTU/ton) sludge solids. The energy use during the two test periods was as follows:

When the results obtained with furnace no. 1 are compared to the historical data the savings fall in the range of 0.9 x 10^6 to 5.7 x 10^6 kJ/mt (0.9 x 10^6 to 6 x 10^6 BTU/ton) sludge solids. When the changes in the control schemes

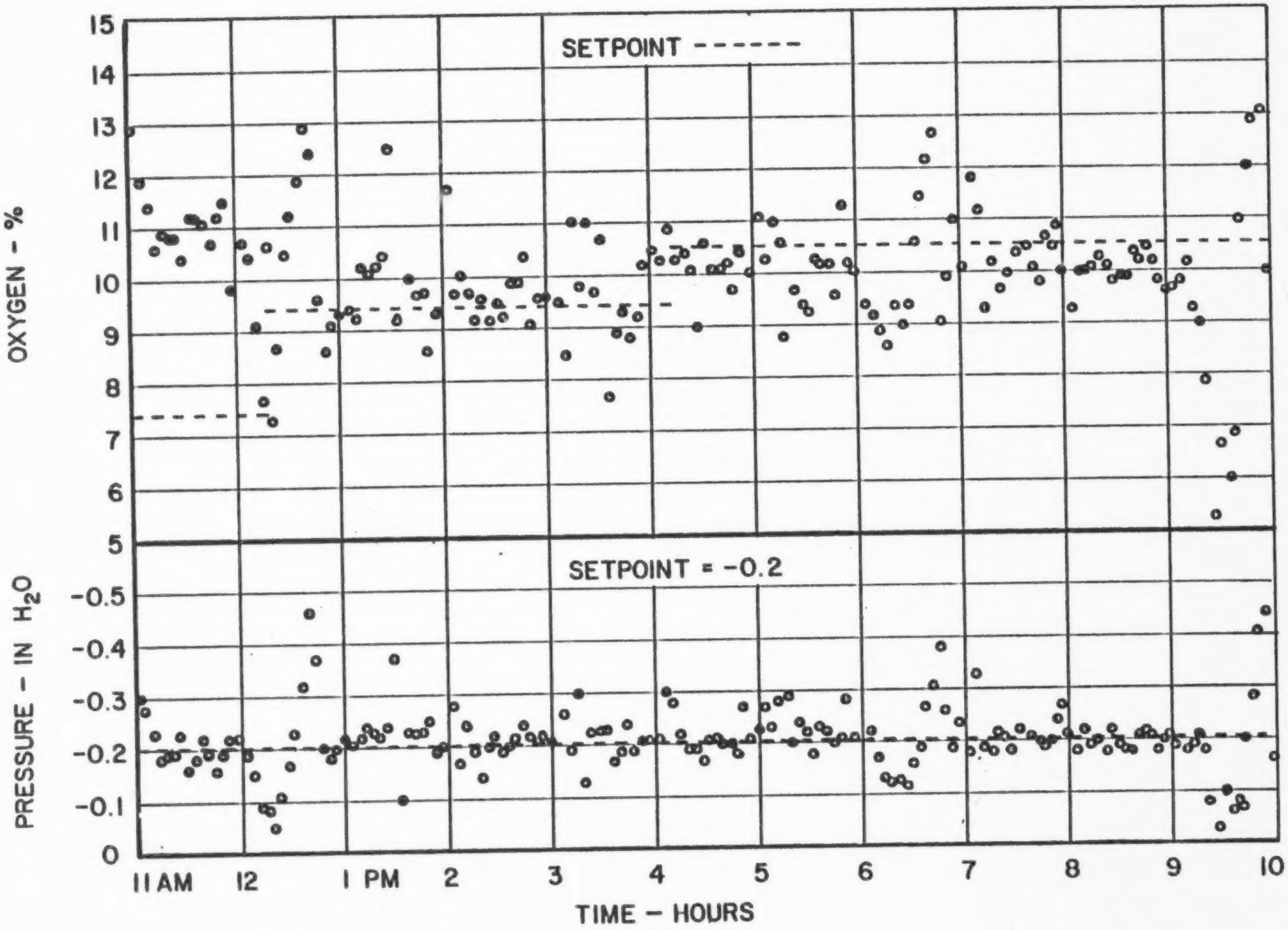


Figure 63. Incinerator pressure and flue gas oxygen concentration for test of June 24, 1981.

between test no. 1 and test no. 2) are considered a savings of 2 x 10^6 appears conservative.

Based on 1981 fuel costs, the annual savings fall in the range of $48,000 to $127,000 depending on the fuel used--natural gas vs oil. Thus if the automated control strategies were applied to both processing trains, the annnual savings for chemicals and fuel would be well over $100,000. It is possible that additional savings would accrue in terms of operating and maintenance time; however, these are difficult to predict.

SECTION 15

HARDWARE EVALUATION

A. GENERAL

The USEPA sponsored a workshop dealing with the research needs associated with the automation of wastewater treatment facilities in September of 1974. The summary of the workshop proceedings (16) listed six major research needs, one being the development of efficient and dependable sensors. Although this observation was made several years ago it is perhaps more relevant in the 1980's because automation of wastewater treatment facilities is a reality. If process control decisions (made by man, analog or digital computers) are to be based on the output of sensing devices, the significance of their dependability is perhaps best summarized by the following old equation in computer technology parlance.

[18] Garbage In = Garbage Out

As outlined in Section 5 the overall objective of this project was to optimize the performance of one of the sludge treatment trains at Seneca. This implies reaching the performance goal at the lowest possible cost. Earlier sections have demonstrated that the control schemes utilized during this project can be used to improve the level of performance and reduce costs for chemicals and energy. The real cost savings, however, can only be determined when the capital and maintenance costs of the control system are considered.

Because this was a research project the initial design of the field monitoring and computer system provided for much more flexibility than required by a system dedicated to process control. A number of the field instruments initially installed did not provide useful data for process control because: (a) instrument failed to function in sludge environment or failed to produce reliable data, or (b) instrument functioned but the parameter was not significant in terms of process characterization. Regardless of the usefulness in this particular project, experience with each of the field instruments is summarized in the followng paragraphs.

B. ON-LINE SENSORS

1. pH

The serviceability of the pipe-mounted electrodes was excellent. Electrodes could be removed, cleaned, and returned to operation in several minutes. On several occasions however, water was discovered inside the transmitter box because of leakage through the electrode seal. Perforated plastic bags filled with dessicant were placed inside each transmitter box to control moisture condensation and rust formation. Other than the occasional water leakage no service problems were encountered with either the electrode transmitters or the control units.

A systematic cleaning schedule designed to prevent fouling was the primary factor in assuring continuous operation of the electrodes during computer control runs. The primary maintenance requirement involved the removal of scale and flocculated material from the electrodes used to monitor the ferric chloride and lime conditioned sludges. Cleaning was normally conducted three times per day for the ferric chloride sludge electrode and more than three times per day for the electrode monitoring lime conditioned sludge. The raw sludge pH electrode was inspected and cleaned approximately once every week.

The electrodes were operable only after the protective shields surrounding the glass bulbs were removed. This significantly reduced the frequency of fouling. Removal of the shields, however, increased the frequency of breakage.

The electrode maintenance schedule was based on data collected during several years of the project. The summary presented in TABLE 27 demonstrates that, when the electrodes were clean, the measured pH of buffer solutions did not deviate substantially from the known value. This indicates that the measurement system, from electrode to local meter and 4-20 ma outputs, was stable. When the electrodes used to monitor the iron and lime conditioned sludges were not cleaned the deviation was substantial; and, it was found necessary to clean these electrodes at frequent intervals to remove the ferric hydroxide and calcium carbonate scale respectively.

2. ORP

The performance of the insertion type ORP electrodes monitoring raw and ferric chloride conditined sludge was similar to the corresponding pH electrodes. Although the protective guards were removed from the electrodes this did not always prevent fouling due to flocculated sludge particles. The electrode monitoring ferric chloride conditioned sludge also received a continuous deposition of ferric hydroxide which was subsequently removed with dilute acid. While in service the ORP electrodes required the same frequency of cleaning as the pH electrodes. Electrode calibrations were not conducted on a routine basis because of the instability of the standard solutions and the tendency for the electrode response to drift during calibration. No problems were encountered with electrical components of the monitors; however, the raw sludge monitor required at least 24 hours to reach equilibrium following electrode cleaning.

3. Solids

Solids analyzer performance was directly related to the variability in the sludge being monitored. Due to the variety of sludge types processed at the Seneca Plant and the variations in mixing and sludge age caused by plant maintenance shut-downs, variations in sludge characteristics were common. The performance of the solids analyzers was adversely affected whenever abrupt changes in sludge characteristics occurred. Based on calibration data and field observations the analyzers would usually provide reliable readings in the solids range of 3.5 - 4.5% solids. When sludge solids fell outside of this range or when partially digested sludge was monitored the reliability of the readings diminished.

TABLE 27. PERFORMANCE SUMMARY FOR pH MONITORS

Electrode	Days Since Calibration	Average Deviation from Buffer pH - pH Units	
		Electrodes Cleaned Prior to Check	Electrodes Not Cleaned Prior to Check
Raw Sludge	1-3	-	-0.02
	4-6	-	+0.02
	7-10	-	-0.02
	>10	-	+0.02
Ferric Conditioned Sludge	1-2	-0.02	-0.24
	3-4	-0.06	-
	5-6	-0.09	-
	7-10	+0.04	-
	>10	0.00	-
	3-5	-	-0.24
	>5	-	-0.24
Lime Conditioned Sludge	1-2	-0.06	-0.3
	4	-0.10	-
	3-5	-	-0.64
	7	-0.04	-
	>8	-0.06	-

Typical performance data are summarized in Figure 64. These data were collected over a 153-day period during which the instrument calibration control was not adjusted. All of the performance data are summarized in TABLE 28. Previous experience with this type of analyzer (17) demonstrated the scatter observed on plots such as Figure 64 is proportional to the length of the calibration period. For example, extremely high correlation can be obtained if the instrument is removed from the process stream and placed in a series of slurries of known concentration within a 1-2-hour period. This was not done at Seneca because there is a tendency for sludge to discharge from the process pipe when the analyzer is removed unless the pipe is almost completely dewatered.

When the length of the calibration period is considered the instruments were judged to perform quite well. The data summarized in Figure 64, however, illustrate that the deviation from the line of best fit can exceed 1% solids. This deviation is substantial and may be excessive for some control schemes. This potential problem was alleviated on this project by correcting the instrument reading using the computer software and the most recent calibration point.

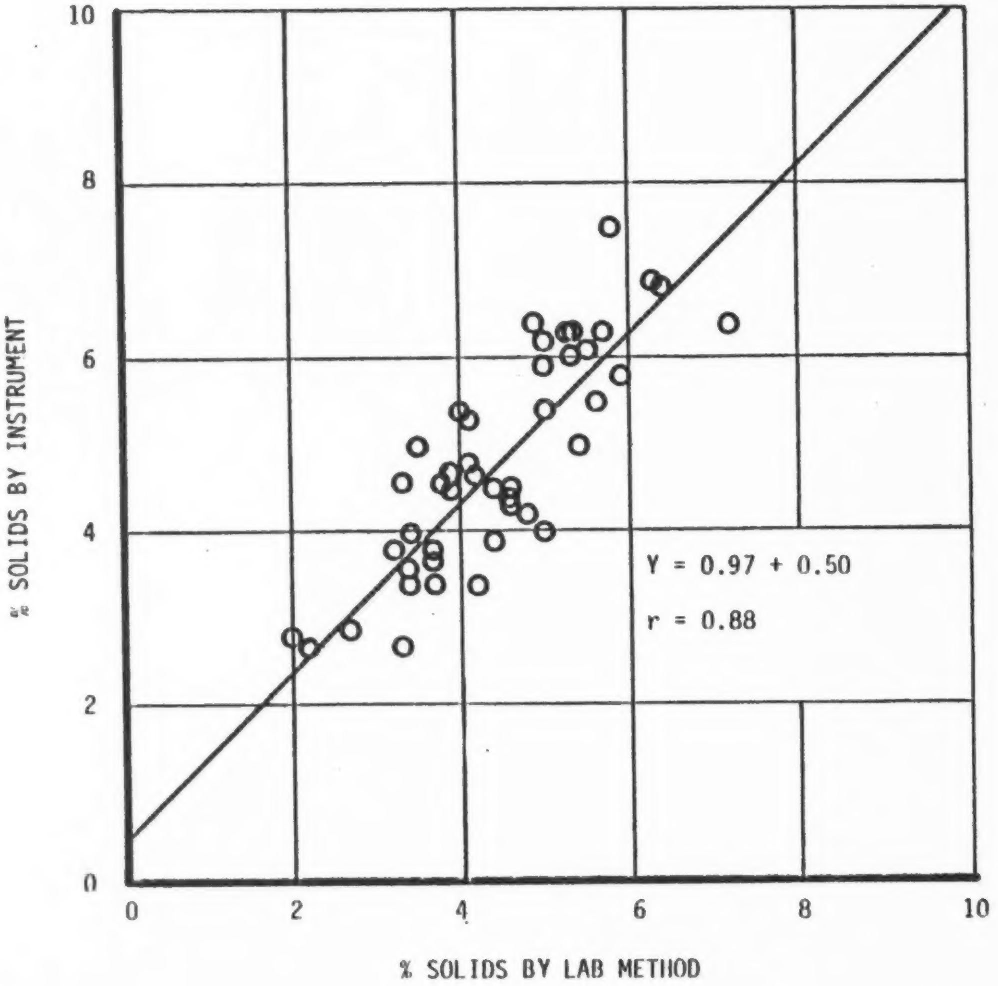


Figure 64. Solids analyzer calibration data collected during a 153 day period.

TABLE 28. SOLIDS ANALYZER PERFORMANCE

Analyzer	Calibration Set	Days	Number of Observations	Regression Analysis Slope	Intercept	r
1	1	224	41	0.94	0.59	0.87
	2	146	37	0.94	0.25	0.88
	3	34	15	0.93	0.36	0.95
	4	93	19	0.92	0.02	0.71
2	1	173	15	0.98	0.09	0.90
	2	40	23	1.01	0.09	0.96
	3	64	27	0.70	0.65	0.87
	4	153	46	0.97	0.49	0.88
	5	69	31	0.84	0.79	0.93
	6	103	22	1.05	-0.08	0.84
	7	92	25	0.96	-0.14	0.91

The maintenance requirements were limited to replacement of the photocell and piston motors in each analyzer.

4. Viscosity

The viscometer was installed in the sludge conditioning tank for evaluation. The rotating spindle was installed in a 122 cm (48 in) tubular baffle. The instrument was positioned just below the surface of the conditioned sludge. An outlet port on the side of the baffle allowed the sludge to flow up through the bottom of the tube, past the spindle, and out the side.

Rags and other stringy debris caused immediate problems. A screen with openings of approximately 1 cm (0.5 inch) was installed at the bottom of the baffle to eliminate that problem; however, the mixing action in the tank was not sufficient to keep the screen clean. In addition to this problem, the spindle and supporting wire rapidly built up a lime scale which increased the drag coefficient of the spindle. The cleaning requirements of the screen and spindle were judged to be unreasonable and the use of the instrument abandoned.

5. Vacuum

Differential pressure transmitters installed on the form and dry vacuum lines of both vacuum filters performed adequately during the filter testing period. Local vacuum gauge readings were used to check the transmitted vacuum signal output to the computer. Operational maintenance was limited to inspection and cleaning of the vacuum ports which accumulated calcium carbonate deposits. Cleaning was required every one to two months. The transmitters operated continuously following initial installation and no additional maintenance was required.

6. Cake Thickness

A sonic type level monitor was installed above the filter drum to measure the thickness of the cake and serve as a warning device for filter upsets. Initial observations detected a substantial drift in the instrument output with time when the sensing head was directed at a fixed target. The addition of a temperature compensator to eliminate possible temperature effects did not solve the problem.

The instrument was returned to the manufacturer for repair and recalibration. Subsequent tests indicated a significant improvement in performance and a number of tests were conducted to determine if cake thickness on the rotating filter drum could be determined. As the drum rotated the average instrument output was determined and subsequently compared to the measured cake thickness. The measured cake thickness was determined by collecting a series of cake cookies from the drum circumference on a line passing under the analyzer. The cookies were stacked; and, the average thickness was determined from the total height of the stack.

The results of the tests are summarized in Figure 65. Part of the scatter was due to the fact that the drum was out of round by approximately 4 mm (0.15 in). In addition it was found that the instrument output drifted about 1.5 mm (0.1 in) per 24 hours. An additional disadvantage of this method of estimating cake thickness is the fact that the cake thickness is not necesarily uniform across the length of the filter drum and the monitor is capable of scanning only a small percentage of the total area.

No further attempts were made to measure the cake thickness directly; however, a calculation routine was developed to estimate average cake thickness from the wet cake production rate and the drum speed. In the calculation it was assumed that the density of the cake was 100 kg/m^3 (63 lb/ft^3) and that no bare spots existed on the drum. Figure 66 illustrates that the calculated thickness provided a reasonable estimate of the average thickness across the drum; and, this method was used whenever a continuous estimate of thickness was required.

7. Cake Weight

Filter cake weight is measured by a load cell positioned beneath the conveyor belt leading to the incinerator. The accuracy of the device is largely determined by the condition of both the belt and its support rollers. Cake buildup on the rollers induces changes in belt tracking which, in turn, causes a lateral shift in cake loading on the weighing device. These changes in loading significantly reduce scale accuracy. It has been observed that the relative distribution of cake on the belt (spread or lumped) also affects scale accuracy. The load cell output signal to the computer was damped to reduce fluctuations in the cake production rate caused by uneven cake distribution.

Electronic instrument calibration included a zero adjustment conducted under no-load conditions followed by a span adjustment conducted with a 9.1 kg (20 lb) weight applied to the scale. Under process load conditions, however, shifts in the belt tracking position caused the instrument calibration to be ineffective. Instrument calibrations were therefore not conducted on a routine basis. The preferred method of scale output correction involved the removal

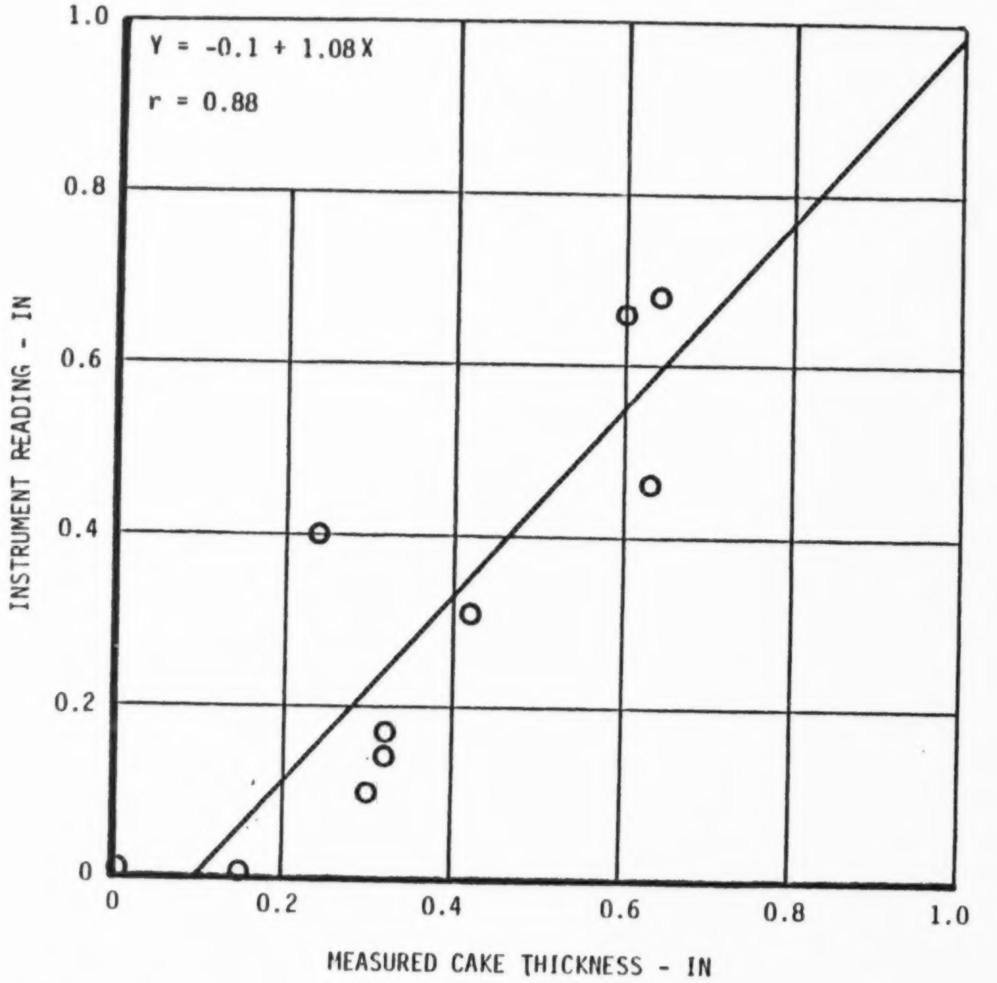


Figure 65. Performance data for cake thickness monitor.

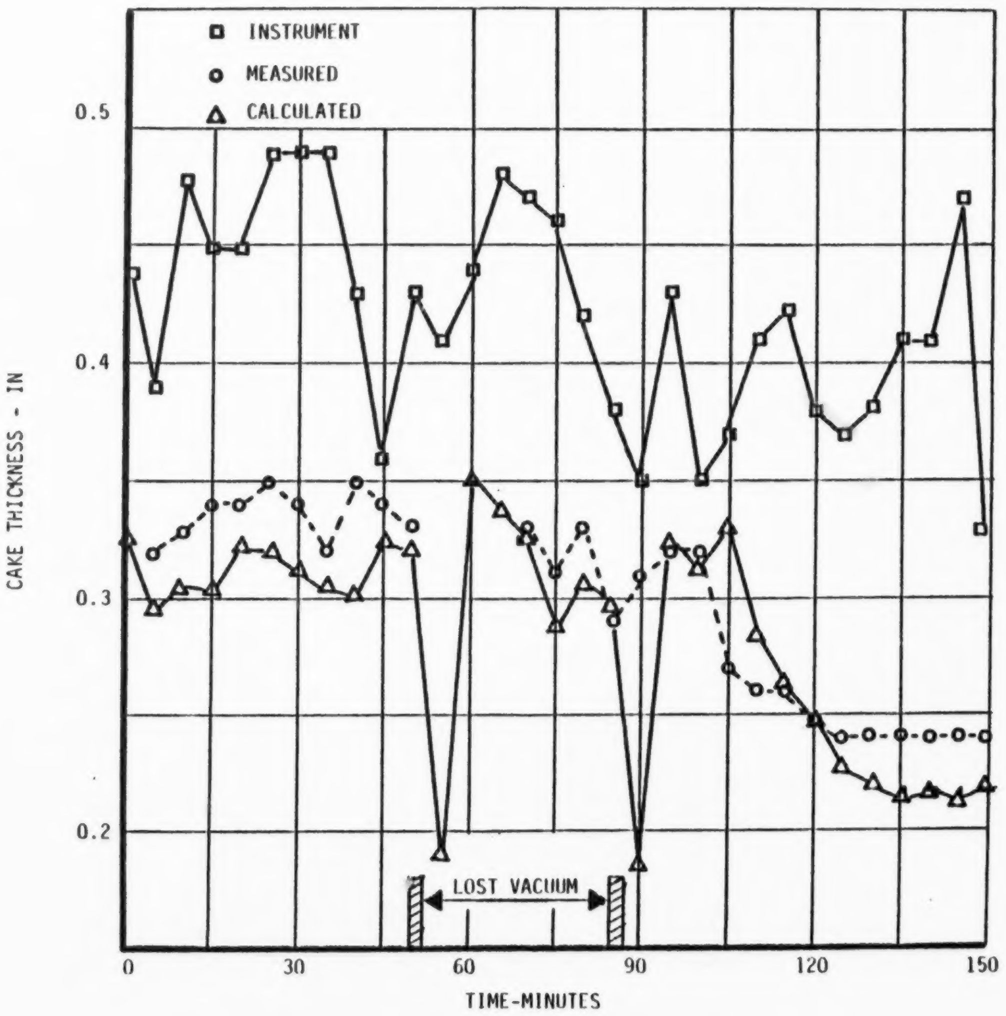


Figure 66. Comparison of cake thickness estimates.

or addition of a number of scale counterbalance weights under process load conditions. Counterweights were removed or added until the scale cake production rate matched the calculated production rate based on cake sampling, filter drum speed and net filter area. Scale counterweights were not changed unless the scale output deviated significantly from the calculated production rate.

The variability in scale output with time is presented in Figure 67. Scale calibrations based on sampling were usually conducted for each filter more than once per week during normal operation. The correction factors were then applied to the computer generated cake production rate.

Based on many field observations and scale calibrations it can be concluded that weigh scales of the type employed at the Seneca Plant can provide reliable production data only under ideal conditions. Day to day shifts in belt tracking or accumulation of filter cake on the support rollers cause inaccuracies in scale readings which cannot be corrected by normal instrument calibration.

8. Cake Moisture

A total of the 16 moisture analyzers were specified for the expansion of the sludge handling facilities at MWCC's largest facility, the Metropolitan Plant. In addition, it was determined that at least one additional instrument would be required on this project to describe the performance of the vacuum filter and to provide feedforward control of the incinerator. Because of this, a number of process moisture analyzers were evaluated at Seneca over a three-year period. The evaluation was conducted at Seneca because access to the filters and conveyor belts was assured. Although the instrument evaluations were not directly related to this project, a summary report is presented below because of the potential impact on-line moisture analysis would have on automated control of both the vacuum filtration and incineration processes.

Initial testing began in 1976 (18) using an infrared instrument mounted on the vacuum filter just prior to the cake discharge. The analyzer was mounted and calibrated by the manufacturer. Although initial test results relating instrument readings to cake moisture content were promising, further testing indicated that the distance between the sample and the sensor influenced the instrument readings. Linear regression analyses of cake moisture analyses and instrument readings produced coefficients of correlation ranging from -0.01 to 0.96 and slopes ranging from 1.8 to 17.2. The results were considered unacceptable and the instrument was returned to the manufacturer. A second infrared analyzer was evaluated in 1977 (19). The instrument was mounted over the inclined conveyor transporting filter cake to the incinerator. Results of 10 tests representing different calibration settings produced coefficients of correlation ranging from -0.94 to 0.98. As observed during the 1976 test, the sample-to-sensor distance influenced the instrument readings. Further testing was discontinued because a constant belt loading could not be attained.

A third test series was conducted in 1978 involving 4 infrared and one microwave instrument (20). The analyzers were mounted in series over the

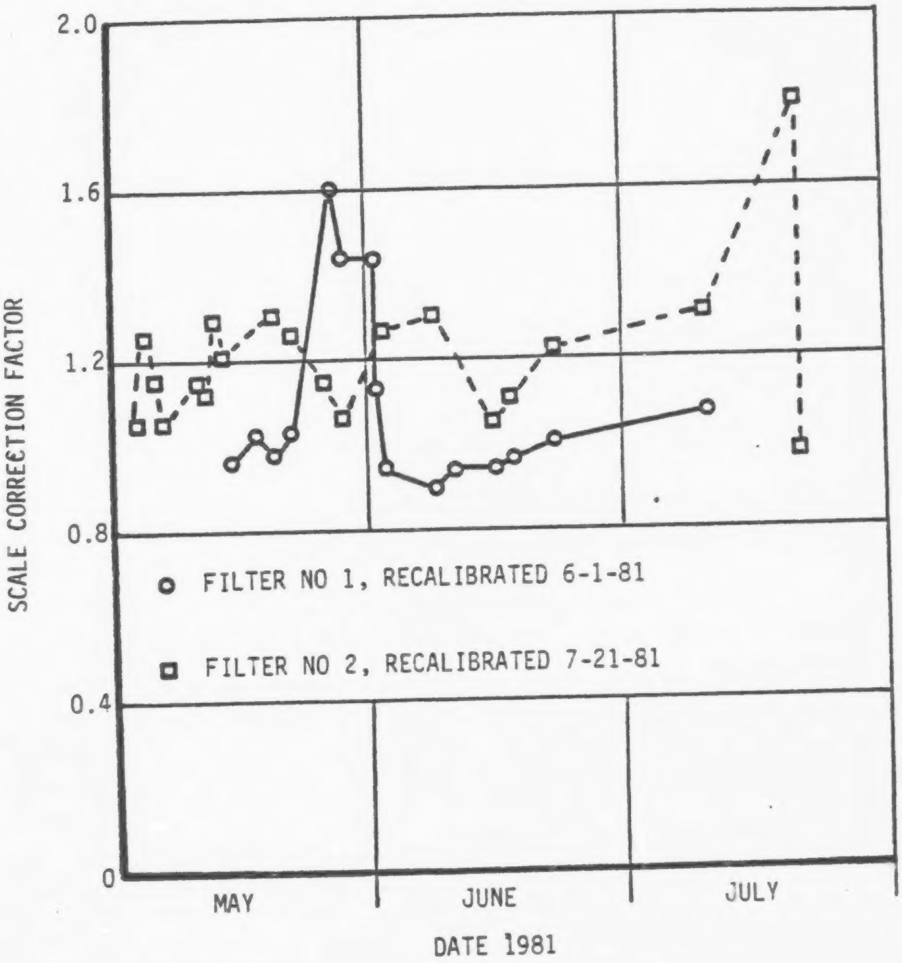


Figure 67. Calibration data for belt scales.

inclined conveyor. Conveyor speed was controlled in order to eliminate bare spots on the belt and to provide a uniform sensing distance. During each test, filter operating parameters were monitored in addition to instrument output. Cake samples were taken from the belt at 30-second intervals over a 15-minute period. Instrument readings were taken every 15 seconds over the same 15-minute period. The average of the cake moisture analyses and the average instrument reading represented one point on the calibration curve. The testing procedure was repeated to obtain additional points under approximately steady state filter operating conditions. Coefficients of correlation for the 5 instruments ranged from -0.30 to 0.54. The data presented in Figure 68, representing the best results, were considered unacceptable.

Additional analyses were conducted in an attempt to relate instrument output to other measured parameters in addition to cake moisture content. These included filter operating parameters, raw sludge characteristics, time and belt loading (an indication of sample-to-sensor distance). As observed in previous tests, the sample-to-sensor distance significantly influenced instrument readings. Linear multiple regression using the 7 most significant parameters produced coefficients of correlation ranging from 0.54 to 0.77. These coefficients indicated that only 30 to 60% of the observed variability could be attributed to the combined influence of the 7 parameters. Further testing was discontinued in order to design a conveying system providing a more uniform sensing distance.

In 1979 a final series of tests involving two infrared analyzers was conducted (21). A positive displacement pump was used to produce a cake sample stream having a flat surface and a uniform thickness. The instruments were mounted several inches above the sample stream which was transported on a small conveyor belt. Cake samples were taken when the instruments exhibited a steady output. Both instruments provided reasonably good estimates of moisture content during individual test runs; however, the individual calibration curves varied significantly. Because of this variation both analyzers were considered unacceptable for process monitoring and control.

In summary, none of the analyzers tested was able to provide a consistent calibration curve from one test run to the next. Test data and field observations have shown that analyzer readings are influenced by parameters other than moisture content. The moisture analyzers tested were therefore not acceptable for measuring filter cake moisture.

9. Vat Level

A sonic type filter vat level monitor with a 91 cm (36 in) measuring range was installed on both vacuum filters. Each installation included a 7.6 cm (3 in) diameter PVC baffle tube to eliminate interfering wave patterns. Results of on-line calibration data for one of the instruments are summarized in Figure 69. The data consist of manually determined sludge levels and the corresponding instrument outputs. Calibration checks were not conducted on a routine basis. Large deviations between the observed level and the instrument output were caused by dried sludge deposited inside the baffle tube. Maintenance requirements consisted of cleaning the baffle tube approximately once per week. No

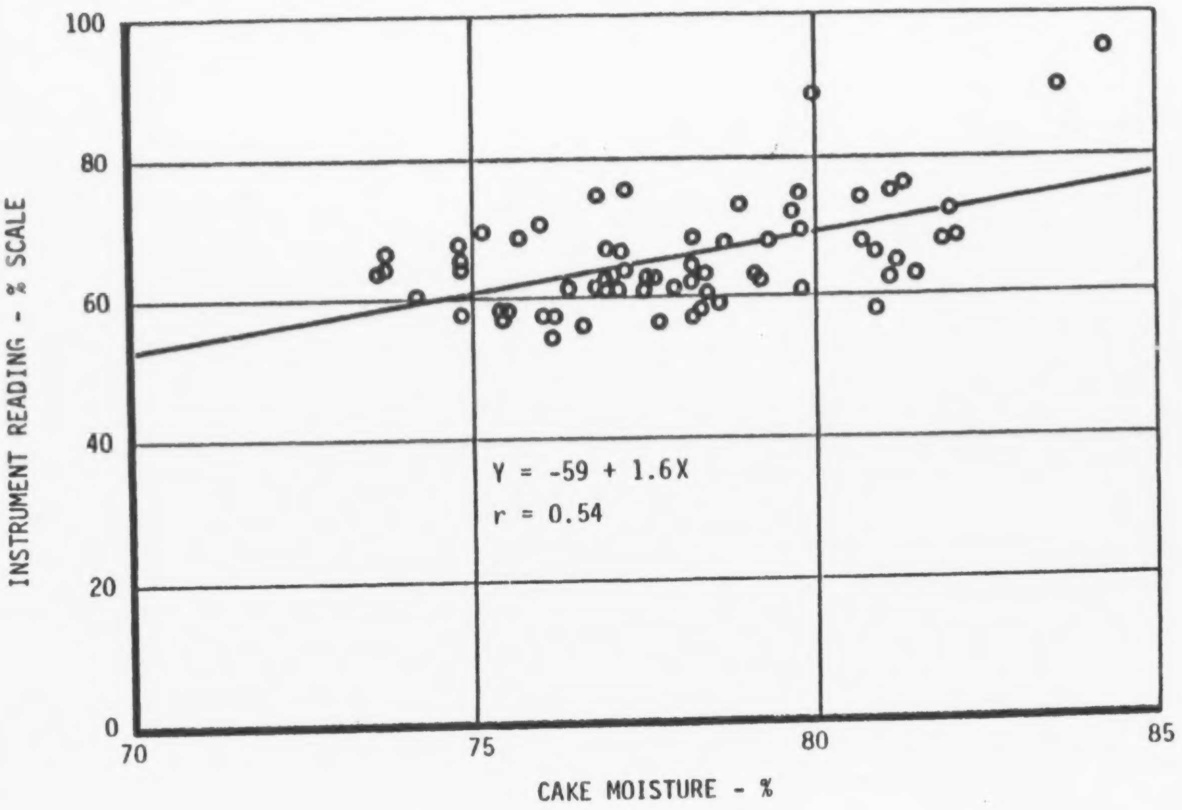


Figure 68. Performance summary for best moisture analyzer of 1978 evaluation.

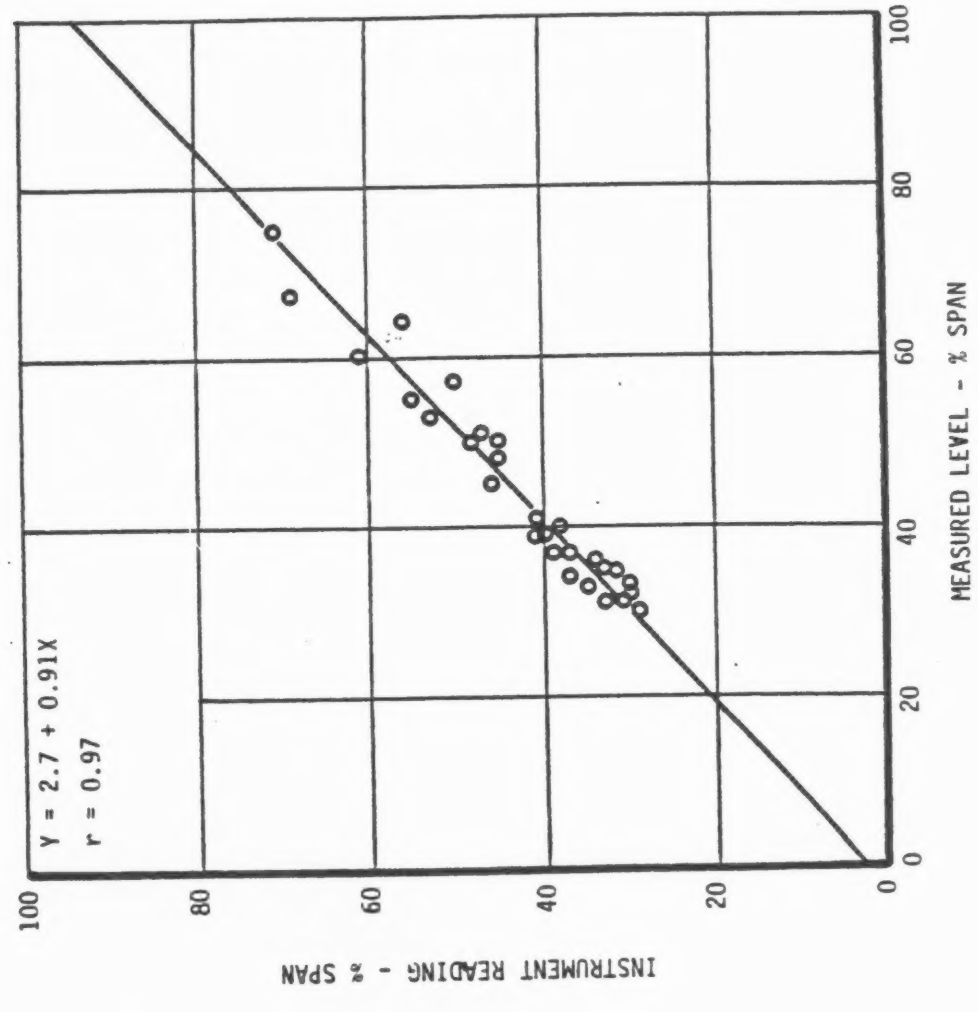


Figure 69. Performance data for vat level monitor.

problems were encountered with the transmitter/receiver or the control unit. The instrument performed satisfactorily, required no maintenance, and is considered ideal for this application.

10. Oxygen Analyzer

The performance of the insitu oxygen analyzer was inconsistent following initial installation in the breech of furnace no. 1 in 1979. Over an 18-month operating period major factory repairs were required on four occasions. An additional repair was conducted at the plant site involving the replacement of the oxygen cell and diffusion element. The primary cause of the failures was attributed to the presence of chlorides and moisture in the incinerator ash which caused corrosion of the external and internal metallic components of the analyzer. Corrosion of these components exposed the sample electrode to refrence gas (air) which in turn, produced erroneously high oxygen readings.

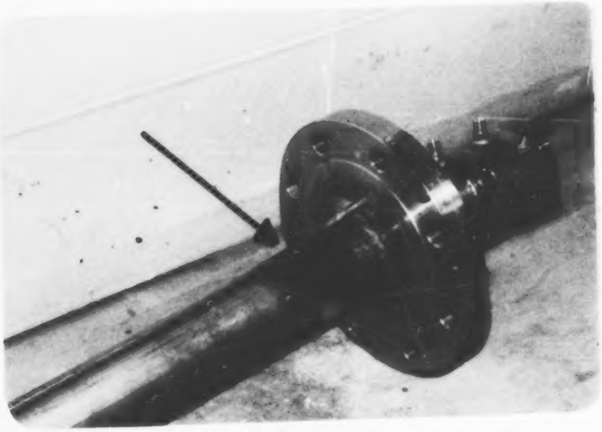
Operating problems encountered following the initial installation and start-up were corrected after several months of operating experience. On two separate occasions failure of the diffusion element allowed incinerator ash to enter the internal cell chamber, eventually causing cell failure. On both occasions the diffusion element was replaced by the manufacturer.

After several months of operation the probe shaft failed due to corrosion--Figure 70a. The corrosion appeared to be related to the accumulation of ash adjacent to the analyzer access port. A stainless steel collar was welded to the shaft by the manufacturer in order to prevent the failure from reoccuring. The external surface of the access port (outside the furnace) was insulated to limit moisture condensation which may have contributed to the corrosion problem.

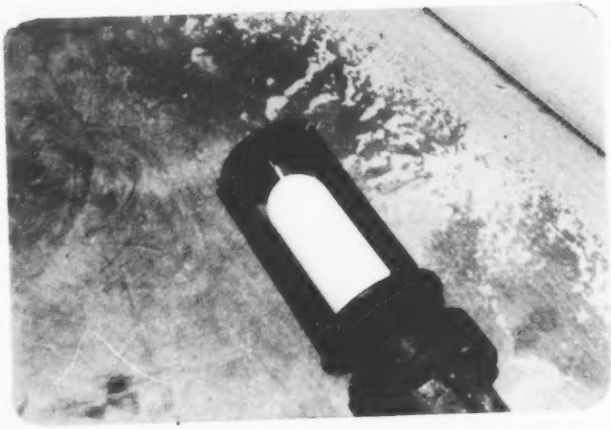
The longest period of continuous on-line operation was approximately 3 months. Although the diffusion element received a thick coating of incinerator ash the deflection plate prevented the element from becoming completely blocked. The buildup of ash did not significantly affect analyzer response time--Figure 70.b.c.

Analyzer output tests conducted during the first six months of operation indicated a zero drift of 0.3% oxygen and a span drift of 0.3% oxygen over a 24-hour period. Both tests met the original specifications; however, later calibrations, using 3.0% and 20.9% oxygen gas (air), usually required minor changes in the instrument zero and span adjustments. During incinerator tests the analyzer was calibrated at least once per day. The probe shaft failed shortly after the field work was concluded in June, 1981. Subsequent to removal it was determined that the stainless steel probe shaft was extremely corroded. Analyses of the corrosion product indicated that deterioration was related to presence of chlorides.

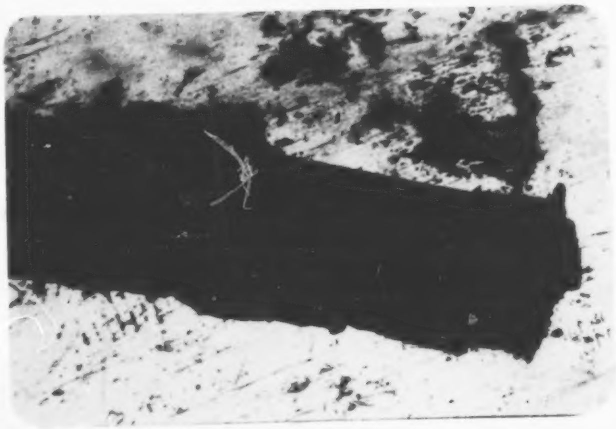
Based on the experience described above the MWCC Engineering Department prepared specifications for two analyzers of the same general type using Hastalloy Alloy C for the probe shaft. Although the instruments are not yet installed it is anticipated that this modification will provide for more reliable service.



(a) SHAFT FAILURE



(b) NEW CERAMIC DIFFUSER



(c) USED CERAMIC DIFFUSER

Figure 70. Oxygen analyzer.

11. Thermocouples

The incinerator hearth thermocouples provided adequate indication of hearth temperature and responded quickly to temperature changes. Thermocouple failures usually resulted from corrosion of the metallic tubes which protect the temperature element from direct exposure to the hearth atmosphere. Failures occurred most often on the burning hearths (no. 3, 4, and 5). The thermocouples were easily replaced and did not require maintenance during normal operation. Although calibration checks of the thermocouple output were easily performed they were not conducted on a routine basis because of the time required and the difficulty of access.

12. Rotational Speed

Tachometers installed for transmitting filter drum, agitator, and conditioning tank mixer speeds operated satisfactorily during the project period. No electrical problems were encountered with the tachometer output signals. Maintenance was limited to inspection and replacement of the spring connecting the motor driven shaft to the tachometer shaft. The springs were replaced whenever below normal speeds were transmitted. The normal operating life for the springs was approximately one year.

Speed calibrations were routinely conducted only for the filter drum. Comparisons of the indicated and measured speed were normally within ±5% range over an operating range of 9-20 RPH. Zero and span correction factors were applied through the computer CRT. Rotational speed calibration checks were conducted approximately once every two weeks.

13. Valve and Damper Position

The incinerator control strategy provided for the monitoring and control of hearth 3 and 5 burner air valves as well as the induced draft, recirculated air, and atmospheric air dampers. Analog output signals from the local position indicators were converted and displayed as percent open at the computer. The computer generated values were calibrated to the local indicators by comparing the computer values to visual observations of the local indicator at different valve or damper positions. The local indicators were also checked against the actual valve position to verify the accuracy of the indicators. Discrepencies discovered between burner air valves on the same hearth were corrected by adjusting the local valve linkage. All burner valves were adjusted so that the controller closed to about one third air flow (12% open). This minimum firing rate eliminated the need to continually restart the burners. All valve positioners responded to computer output signals as required during incinerator control tests.

14. Flow Meters

The raw sludge flow meters serving the vacuum filters were calibrated on eight occasions over an 18-month period. The calibrations were conducted by filling the conditioning tank during a measured time period and comparing this calculated flow rate to the flow totalizer readings for the same time period.

On three occasions the difference between the calculated and indicated flow exceeded 38 l/min (10 gpm) and on one occasion the difference exceeded 76 l/min (20 gpm). Correction factors, based on the calculated flows, were applied to the flow values through the computer. The cause of the discrepancies was not determined. Electrical calibrations of the flow totalizers are performed by plant personnel on a yearly basis. The flow sensing elements were not inspected during the project period.

15. Holding Tank Level

The performance of the sonic-type sensors employed for measuring sludge levels in the holding tanks was unsatisfactory following their initial installation in April, 1979. The sensors were factory calibrated to provide level measurements over a range of 0-12 m (0-40 ft). Although the sensors provided relatively accurate readings for several days, on other occasions the readings were substantially different than manually measured levels. Performance data collected during 1979 are presented in Figure 71. In several instances the instrument readings were off-scale and could not be compared to measured levels. After 7 months of operation the sensors were returned to the manufacturer for inspection and recalibration. The sensors were returned by the manufacturer and reinstalled in March, 1980; however, problems with erratic readings were encountered. Both sensors were removed and calibrated according to the operating instructions using 4 x 8 ft wood target. Although the performance of the sensors improved following the calibration, off-scale readings were later observed on a number of occasions. Additional recalibration of the sensors did not prevent the erratic performance. When the sensors failed to respond to calibration adjustments in July, 1980, their performance was no longer monitored.

The cause of the inconsistent performance was not identified. Moisture and ice accumulation in the sensors may have caused erratic performance during the colder months; however, inaccurate readings were also observed during warm periods. The air diffusion pipe network located near the base of the holding tanks may have produced interferences in the wave pattern causing erratic readings. The presence of the air diffusion pipes, however, cannot explain the inaccurate readings obtained at high sludge levels. The calibration failure was likely due to a component malfunction in the control units.

Based on the performance of the sensors and the calibration problems encountered they are not recommended for applications similar to those described.

16. Turbidity

Following the design and installation of a vacuum filter filtrate sampling and debubble system, on-line studies were conducted which compared the turbidity readings of the surface scatter instrument with those of a laboratory instrument (Hach Model 2100 A). Calibration of the on-line instrument was performed using a 740 NTU calibration plate supplied by the manufacturer. The comparison data, presented in Figure 72, produced a correlation coefficient of 0.73.

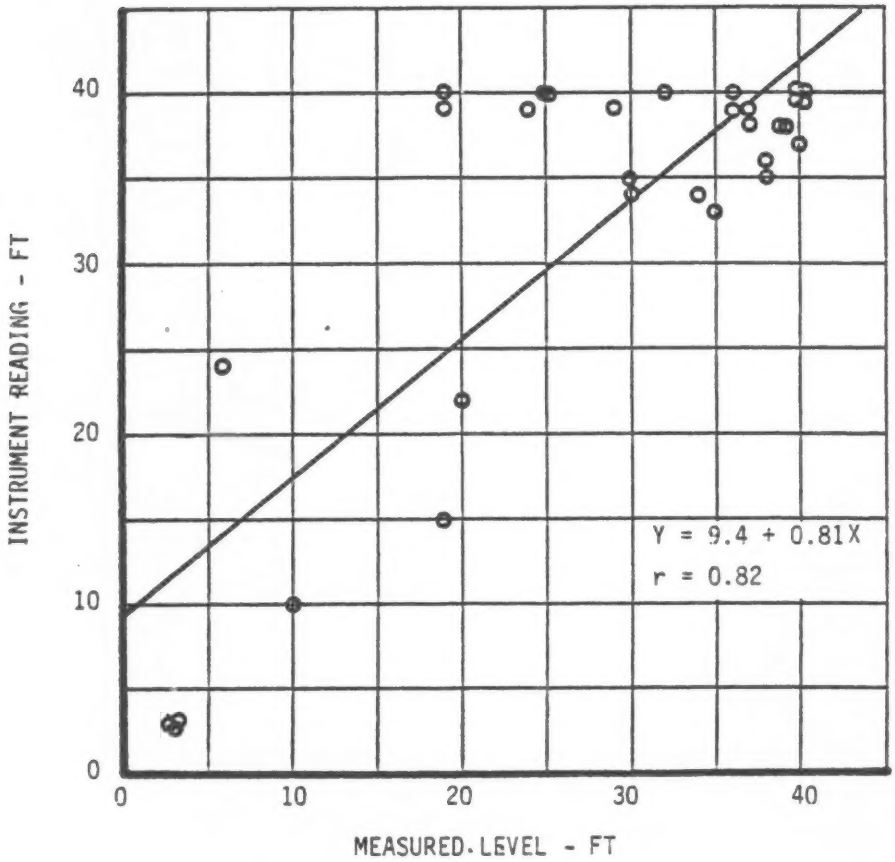


Figure 71. Performance data for holding tank level monitor.

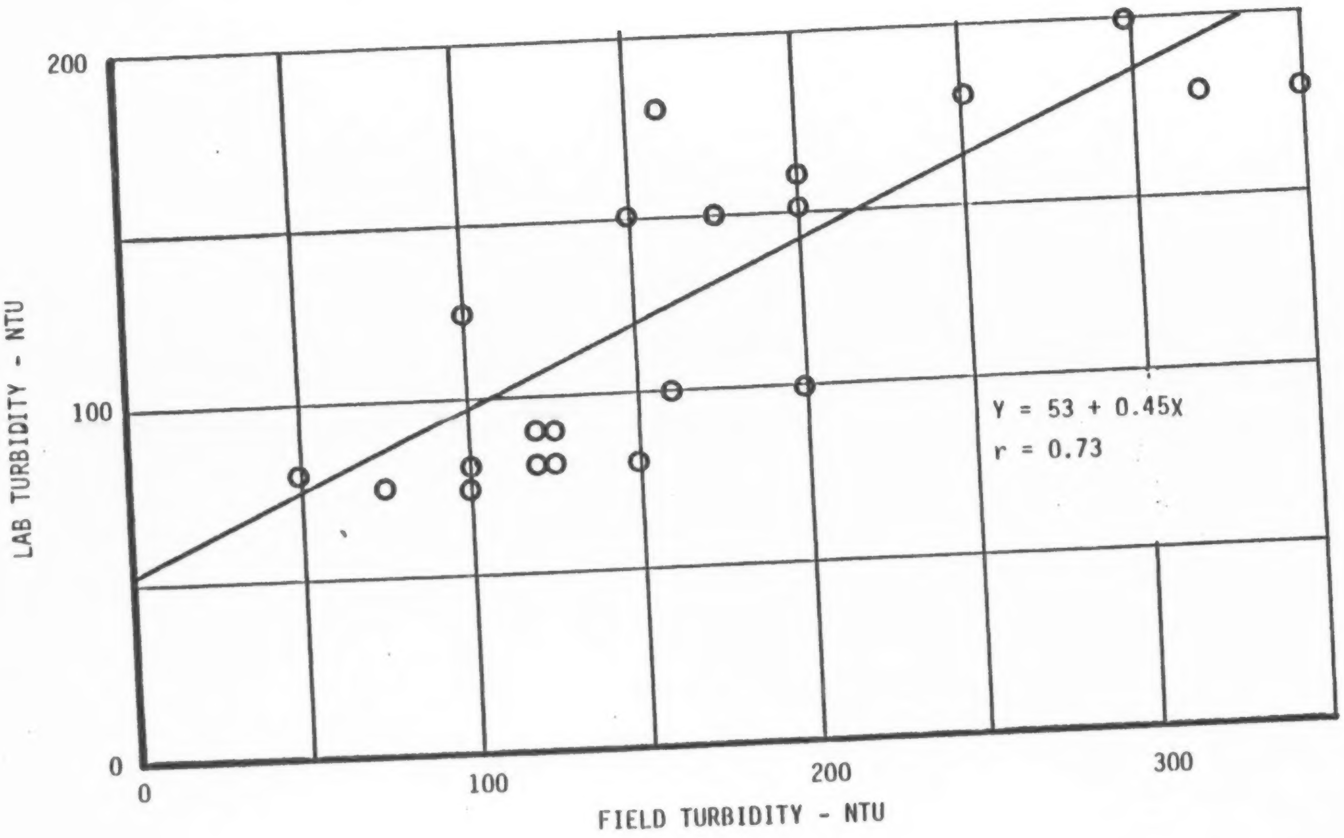


Figure 72. Performance data for turbidity monitor.

The debubble chambers and sampling lines required frequent cleaning in order to provide a reasonably consistent flow of sample which was necessary for optimum instrument performance. A continuous buildup of scale on the inside of the sample lines served to restrict the flow of sample due to increased head loss. Intermittent carryover of foam to the turbidimeter was also a continuing problem. It was determined that the level of maintenance required to supply a filtrate sample suitable for on-line monitoring would offset any process information gained from filtrate turbidity measurement. Further testing and evaluation was therefore discontinued.

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APPENDIX A

DEVELOPMENT OF A COMPUTER BASED CONTROL SYSTEM

A. COMPUTER SYSTEM DESIGN

1. Design Considerations

The design of the computer based control system was predicated on the needs of the research goals of the project. The most significant objective was to provide a demonstration of a highly automated vacuum filter and to gather data indicating the cost-benefit picture for this automation. Fundamental to the demonstration was the development and testing of various control strategies and process models. Flexibility was highlighted as an extremely important consideration in the control system design, because of the developmental nature of the project.

Other design considerations evolved as prelimary investigations of the vacuum filter began. It was determined that the basic tasks of the project; data collection, model verification and control loop tuning, would be done by engineering personnel and their assistants. The operational priorities and normal duties of the plant operators made it difficult to involve them in the design and research areas of the project. Therefore, the second major design consideration was to develop a control system that engineering level people could use, modify and operate to accomplish the automation goals.

The existing control system, installed when the plant was built in 1970, was a typical control panel based system. To protect this equipment, the controls were enclosed in a glass walled control room located on the operating floor between the vacuum filters and incinerators. The level of control capability on the panels was minimal from an automation perspective. The existing panel capabilities and the space limitations inherent in the glass walled control room became the third major design consideration.

Based on these considerations, a computer based control system approach was selected as the most suitable for the project goals. The computer based approach offered the following advantages:

- Minimal interfacing and modifications required on the exsiting control panels. No electrical rewiring by trade electricians necessary for the modifications to control strategies under development. This approach eliminated the problem of inflexible control panel systems.
- Minimal interference or disruptions to plant operations during testing or monitoring.

- Maximum flexibility to modify control strategies through engineering level programming.
- Extensive and comprehensive data monitoring and gathering capabilities.
- Minimal additional equipment located in the Sludge Disposal Building control room.

The project did have financial and calendar constraints on large one time purchases that also effected the system design.

2. Location Considerations

The selection of the location of the computer based control system was based on three factors: 1) environment, 2) available space, and 3) cost. Three alternatives were explored:

- Enlarge the control room to make space for the computer based control system. This approach was abandoned because of the physical problems (space, air conditioning, etc.) of enlarging the control room.
- Build a separate room nearby to house the computer system. This approach was also dropped for the same reasons as above and due to cost.
- Locate the computer system in the Administration Building (already air conditioned and housing computer based systems). This is the approach that was selected.

The selection of a computer system site remote from the process implied a split or distributed design for I/O interface. A cost analysis indicated that a Remote Terminal Unit (RTU) located near the control panel that would multiplex the process signals from the panel over a single pair wire to the "central" computer was more cost effective and more flexible than hardwiring each signal to the computer. Figure A1 shows the central computer room layout in the Administration Building. Also shown is the control room in the Sludge Disposal Building and the associated RTU and interface equipment.

3. Interface Considerations

The design of the computer based control system required that Vacuum Filter Control devices be remotely controllable and that sensors, either existing or added, be monitored for data gathering and control. Seven control devices were identified on the Vacuum Filter as being potentially effective control points. Each control device was equipped with a computer-local selector switch located on the control panel through which control of the device could be transferred from the panel to the computer.

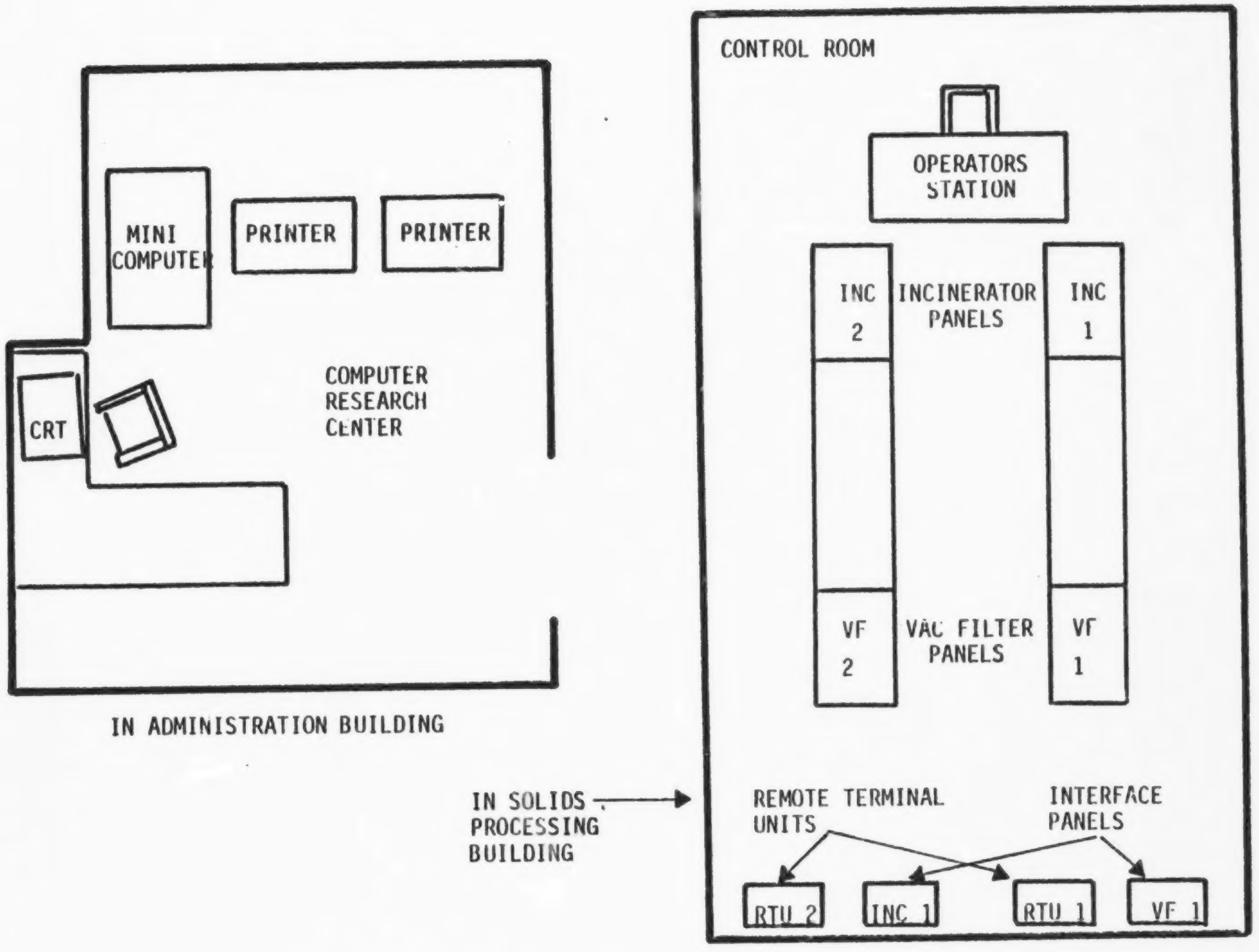


Figure A1. Layout of control hardware.

In this manner, the control strategy for each device could be tested individually. Signal converters were used to provide current loop interfaces to the RTU from the existing panel instrumentation. New sensors as described in other sections were interfaced directly to the RTU as the units were obtained with current loop type outputs.

4. System Configuration

Preliminary determinations of the number of signals needed by the control system for steady-state control indicated that a relatively small computer (by 1977 standards) would provide the functions required. Since future project requirements were unclear and since microcomputer systems were not proven for process control system applications at that time, a specification for a small minicomputer based system was prepared. A black and white CRT with keyboard was selected for the operations console. A line printer with keyboard was utilized for hardcopy functions. A moving head disk system was required for data and program storage. Figure A2 shows the detailed original computer system configuration that was procured through standard bidding procedures. Other computer system suppliers that participated in the selection process included Digital Equipment Corp., and Honeywell. Data General Corp. was the low bidder and therefore supplied the system. Peripherals were purchased separately.

B. COMPUTER SOFTWARE DESIGN

1. Overview of the System

The central computer is a Nova 3 minicomputer using the RDOS 6.33 operating system. The configuration is shown in Figure A2. Process I/O is collected and transmitted to the Nova system by remote terminals using microcomputers to process and mutiplex the data.

The central computer software memory map is shown in Figure A3.

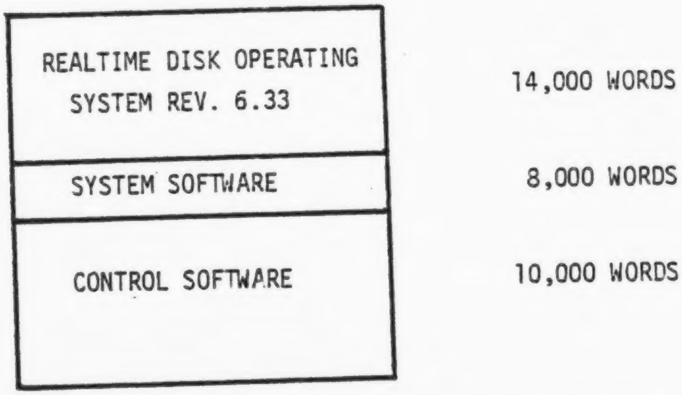


Figure A3. Memory Map

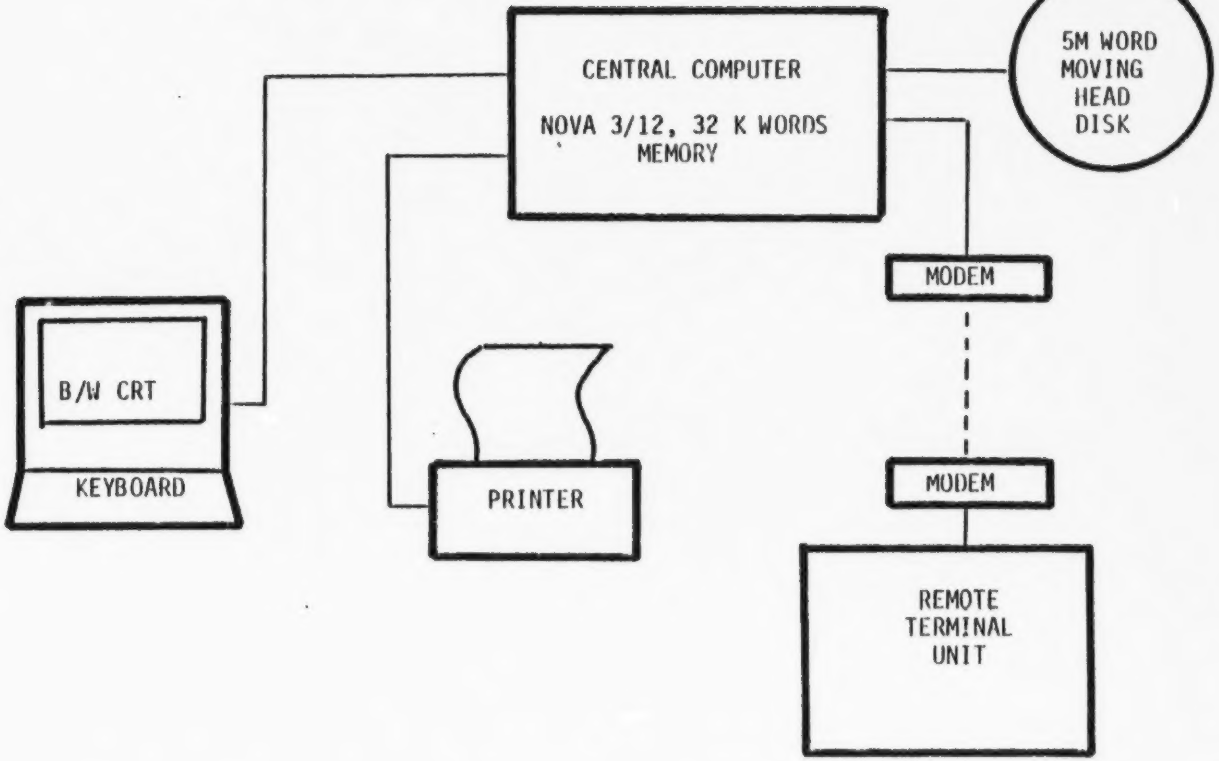


Figure A2. Computer system configuration.

The program block sizes are estimates only. The Real-Time Disk Operating System (RDOS) is a standard software package available from Data General Corp. The system software is comprised of three major programs that make possible two important items in the control software; a programming language for engineers, and a data structure that provides the framework for the control software. The system software is written at the assembly language level for efficiency both in size and speed. The control software uses the data structures established by the system software in which to define I/O point records and uses the programming language to provide algorithms that are capable of process control.

2. System Software Design

The software package consists of three major sections: 1) operator interface routines, 2) interpreter/scanner, and 3) data base generator as diagrammed in Figure A4. The operator interface routines establish an operator/computer protocol which enables the operator to issue system control commands and solicit parameter data. The interpreter/scanner acts upon the established data base which defines all points in the system and specifies all mathematical equations required to implement the control algorithms. The data base generator is used to convert programming language statements into an interpretive binary code format which then becomes the established data base. A general description of each software module follows:

a) Operator Interface Routine

The operator interface routine is responsible for establishing an operator/computer protocol. This protocol allows the operator to communicate and control the system environment by entering a series of commands on the operators console (ADDS 580 CRT). The software responds to these commands and act upon them. Format errors are detected and result in operator error messages.

Change System Parameters:

- Point name-scan status
- Point name-parameter data (error limits, deadbands, gains, etc.)

Print System Parameters:

- Point name-scan status
- Point name-parameter data

System Commands:

- Start/stop scan
- Load data base
- Printer control

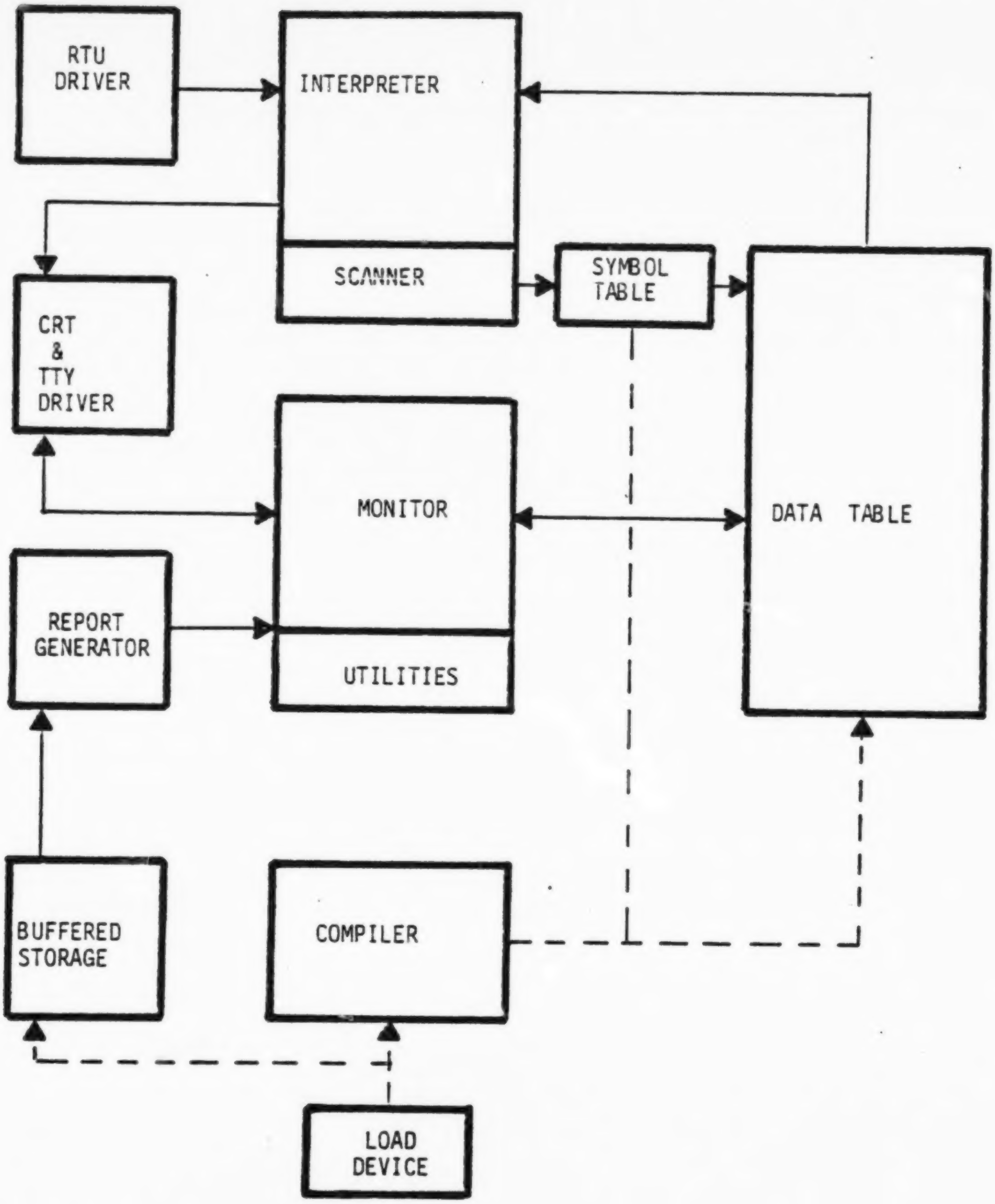


Figure A4. Layout of control software.

In addition, a command is provided that allows the operator to generate and print a variety of reports. The reports are generated by a report generation routine which is also used to generate CRT and printer overlays when a system print command (parameter data) is issued.

b) Interpreter/Scanner

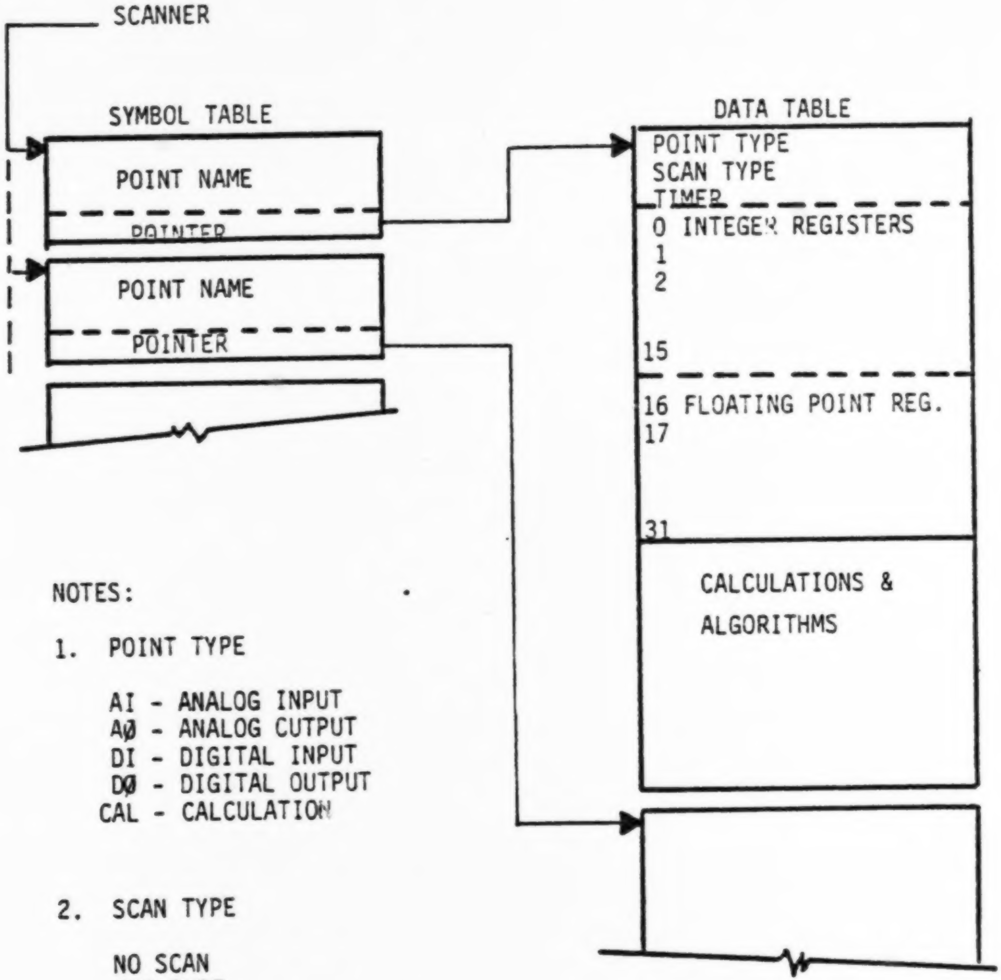
The interpreter/scanner is responsible for scanning all points in the system and processing all algorithms associated with currently active points. Control algorithms are defined as a sequence of mathematical equations which are serviced by the interpreter routine. The interpreter is capable of processing equations which contain addition, subtraction, multiplication, division, logical OR, logical AND, and logical exclusive OR operators. All logical operations are restricted to 16 bit integer operations while all other operators can be used on mixed 16 bit integer and floating point data words. In addition, the interpreter can process general purpose commands that are used for conditional branching, subroutine calls, direct calls, data formatting, printing report generation, and scan control.

The scanner routine when activated by the operator, will sequentially scan a table containing the alpha-numeric names of all points in the system. These point names can be associated with analog inputs, analog output, digital inputs, digital outputs, calculators, and data buffers. When the scanner detects that a point is ready for execution (i.e., algorithm execution), control is passed to the interpreter which then acts on the algorithm associated with the current point. The scanner determines if a point is to be activated (algorithm execution) on a timed interval, once every pass through the scan table, or one time only.

c) Data Base Generator

The data base generator is responsible for converting programming language statements (generated by engineer) from a disk file and creating a core resident data base table (see Figure A5). The table contains all data necessary to define each point in the system and all algorithms associated with each point. The source code input is checked for entry and format errors, each error will result in an error message printed on the operator's console. The source code input allows the engineer to:

- o Define alpha-numeric point names and assign scanning requirements.



NOTES:

1. POINT TYPE

   AI - ANALOG INPUT
   A0 - ANALOG OUTPUT
   DI - DIGITAL INPUT
   D0 - DIGITAL OUTPUT
   CAL - CALCULATION

2. SCAN TYPE

   NO SCAN
   ONE SHOT
   TIMER (1 SEC - 34 MIN)
   EVERY SCAN

Figure A5. Data base structure.

- Design and implement control strategies utilizing flexible mathematical equations.
- Design and create report generation routines.
- Design and create data retrieval and storage routines for subsequent report generation.

The data base is created by utilizing a procedural control language that has been designed for the purpose of describing alpha-numeric point names and their associated parameters (scan data, algorithms, etc.). The source statements that represent this language are placed on a disk file utilizing the text editor. Once the source statements are on disk, they can be changed/modified using the text editor.

3. Control Software

The control software has been designed as modular units. The required control functions have been identified and designed as subroutines using the language just described. The process control functions include subroutines for analog inputs, linear compensators (a routine where inputs from more than one point are weighted and combined to produce the controlled output), ratio controllers, lead/lag controllers, PID controllers and outputs (analog and incremental).

An example of these routines is the PID controller subroutine. The deviation of the process variable from a setpoint is used in the calculation of the standard velocity PID equation. The subroutine can be made into a positional PID equation by calling the analog output subroutine which adds the change in output to the previous output. The setpoint and the proportional, integral and derivative gains can all be changed by the engineer from the CRT for tuning or by other control programs for adaptive control. The PID tuning capabilities include storing in a register the calculated value of the Integrated Error and Integrated Squared Error.

4. Performance

The original software design assumed that the entire data base would be core resident. Although this limits the size of the data base that can be used, it allows very efficient execution times. Internal scan rates can be set to tenths of seconds and points can be set to run on 1 (one) second scan rates. The screen is refreshed at 1 (one) second intervals although if overlays are called, it takes an additional 1 or 2 seconds. The remote terminal is scanned every 3 or 4 seconds, so every 3 or 4 seconds all values can be updated.

C. REMOTE TERMINAL DESIGN

1. RTU Functions Required

The remote terminal design included the specification of input/output interfacing equipment and the communications protocol to the central computer. Five types of interfaces were identified; analog inputs, digital inputs, analog outputs, digital outputs and timed (pulsed) digital outputs. The first four are standard industrial interfacing systems. The timed output provided a simple interface to incremental (increase-decrease) control devices. The RTU receives a value in seconds from the central system that the timed digital output is to be held closed. The RTU then energizes the relay, times out the duration, and de-energizes the relay after the requested number of seconds has elapsed.

The rules for using the communication line between the central computer and the RTU are collectively called the protocol. The major features of the protocol design included a 16 bit cyclic redundancy code type of error system for detection of line errors. Otherwise the protocol is designed to be a straightforward master-remote (slave) arrangement.

2. RTU Design Limitations

The limitations on the RTU design occurred in several areas. The RTU location was chosen to be as close to the panel as possible to minimize wiring. Thus the unit was designed for wall mounting in the control room. The line speed was determined to be 1200 baud (120 characters per second) based on the number of points, the line protocol overhead estimates, and the cost differential to go to a faster speed. The number of input-output points for spares and expansion was determined based on protocol limitations, and physical space limitations. Since the RTU was specified as a separate item from the computer based equipment, the specification outlined the limits of responsibility for the supplier which included all equipment up to the interface card in the central computer. The software driver at the central computer was not part of the supplier's responsibility and was written after the RTU equipment was built.

3. RTU Signals

The connected signal for RTU no. 1 and no. 2 are presented in TABLES A1 and A2.

D. MODIFICATIONS FOR LARGER I/O BASE

1. Configuration Modifications

The original system was modified by the addition of a second multiplexer for the incinerator control. Also an alarm/event printer, timeshare terminal, and a modem for a phone link to the University of Minnesota Computer Center were added. The modified computer configuration is shown in Section 7.

TABLE A1: MUX #1: DEWATERING PROCESSES

ANALOG INPUT POINT NAMES

AI#	Point Name	Description
0	FL1R	Flow VF1 raw sludge
1	PHR	pH raw sludge VF1
2		
3	PHF	pH ferric sludge VF1
4	L1FL	Lime flow VF1
5	PHL	pH lime sludge VF1
6		
7	SS1R	Suspended solids VF1 raw
8	FL2R	Flow VF2 raw sludge
9	VAT1	Vat level VF1
10	VAT2	Vat level VF2
11	L2FL	Lime flow VF2
12	WT1	Cake weight VF1
13		
14	WT2	Cake weight VF2
15	SS2R	Suspended solids - VF2 raw
16		
17		
18	F1FL	Ferric flow VF1
19	F2FL	Ferric flow VF2
20		
21		
22		
23		
24		
25		
26	D1ST	Drum speed VF1
27	D2ST	Drum speed VF1
28	A1ST	Agitator speed VF1
29	A2ST	Agitator speed VF2
30	DRY1	Drying zone pressure VF1
31	DRY2	Drying zone pressure VF2
32		
33		
34	HT1L	Holding tank 1 level
35	HT2L	Holding tank 2 level

TABLE A2: MUX #2: INCINERATION PROCESS
ANALOG INPUT POINT NAMES

AI#	Point Name	Description
0		
1	AMBZ	Ambient air damper
2	O2	Oxygen in stack gases
3		
4	RCAZ	Rabble arm cooling air damper
5		
6	IDFZ	I.D. fan damper
7		
8		
9	H3Z1	Hearth 3 burner damper 1
10	H3Z2	Hearth 3 burner damper 2
11	H5Z1	Hearth 5 burner damper 1
12	H5Z2	Hearth 5 burner damper 2
13	H6Z1	Hearth 6 burner damper 1
14	H6Z2	Hearth 6 burner damper 2
15		
16	RAST	Rabble arm shaft speed
17	H1T	Hearth 1 temperature
18	H2T	Hearth 2 temperature
19	H3T	Hearth 3 temperature
20	H4T	Hearth 4 temperature
21	H5T	Hearth 5 temperature
22	H6T	Hearth 6 temperature
23	H7T	Hearth 7 temperature
24	DFTP	Furnace draft pressure
25	SRDP	Scrubber differential pressure
26	OIL1	Fuel oil to incinerator 1
27	FUE1	Fuel oil from incinerator 1
28	GAS1	Natural gas to incinerator 1
29	OIL2	Fuel oil to incinerator 2
30	FUE2	Fuel oil from incinerator 2
32	RCAT	Rabble arm cooling air temperature
33	SRIT	Scrubber inlet temperature
34	IDFT	I.D. fan temperature
35		

2. Data Base Swapping Facility

With the addition of a second remote multiplexer, the data base became too large to be core resident. A data base swapping facility was provided to swap sections of data base between the core memory and disk memory and is organized as follows:

a) Data Base Swapping

Memory allocation associated with the data base swapping facility consists of multiple modules each having a variable size. Each module is a multiple of 256 words and has a corresponding map in resident memory. Module size is determined by the data base configuration, which provides the programmer with the ability to organize the data base for maximum process throughput. Data base size is limited only by the available storage of the disk pack. A swapping algorithm is designed to alleviate system contention by utilizing a priority scheme associated with each interpreter task. The criteria for swapping the modules is described in the following section.

b) Symbol Table Swapping

Each module has a corresponding map in resident memory and indicates the priority of system usage (interpreter tasks). Again a swapping algorithm has been designed to alleviate system contention by utilizing a priority scheme associated with each interpreter task. Loading and swapping criteria for four modules is as follows:

1) Upon system load, all four modules are loaded with the first 168 symbol table entries. The lowest user priority is assigned to each module.

2) If an interpreter task requests a symbol entry that is not contained in any of the four modules, the following priority scheme is used (see examples):

   *If a caller has priority #N (0 high, 3 low), then any module with priority N+1 or lower is swapped with the requested symbol table segment.

   *If a caller has priority #N and all modules have priority N+1 or higher, then caller is suspended until a module is released.

   *If a caller has priority #N and all modules have multiple outstanding priorities of N or lower, then the module with the least number of users (N+1 low, N high) is swapped with the requested symbol table segment.

3. Multi-Tasking Interpreter

A multi-tasking interpreter facility was implemented and enables the present scanner/interpreter software to schedule four (4) simultaneously executing interpreter tasks. Each task is assigned a priority number and a system loading number (see examples) which are obtained from their respective header blocks. This information is entered into the data based by the programmer and provides a means of directing system loading and throughput. Task priorities are utilized for the purpose of scheduling system resources. System loading numbers are utilized for the purpose of excluding concurrent execution of certain interpreter tasks.

4. Remote Multiplexer Interface

A remote MUX interface facility was implemented and enables the CPU to communicate with both remote multiplexers. Access to alarm conditions (poly, time-out, and compare errors) in both remote units is made available to the application programs by the addition of a status command in the interpreter/compiler. Modification of the exisiting point name identifier sequence was made to include a separate field which is used to identify the remote MUX associated with the indicated I/O channel number.

5. Performance

Since the modified software now swaps portions of the data base into core memory from the disk memory, the data base size is limited only by the size of the disk packs. The internal scan rates are still set in tenths of a second, although the point algorithms execution and screen refresh rates are limited to about 5 seconds. The remote terminals are scanned and all values are updated approximately every 10 seconds. The point algorithms' execution rate and the screen refreshing rate may be further improved through a more optimal choice of priority and load number assignments.

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge				Cake			Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
001	724	16	81	5.61	-344	3.33	4.65	122	15.7	11.92	24	20	94	15.5		4.09	23.1	4.9	16.0	51	COM
002	724	17	94	5.62	-331	3.35	4.94	93	13.9	11.95	19	20	106	15.7		4.14	20.9	5.0	15.0	52	COM
003	724	18	103	6.07	-312	3.29	4.81	113	16.4	11.86	15	20	115	19.8		5.39	22.6	15.9	15.9	53	COM
004	724	19	95	6.05	-305	3.42	4.26	168	18.5	12.00	25	20	111	18.1		5.34	19.7	10.3	14.9	54	COM
005	724	20	100	5.98	-262	3.57	4.96	130	13.9	11.97	17	20	112	20.1		4.87	26.8	12.8	12.8	55	COM
006	724	21	110	5.92	-285	3.67	5.05	70	14.4	11.87	16	20	124	19.1		5.28	23.3	17.4	16.0	56	COM
007	724	22	83	6.01	-257	3.38	4.65	112	17.5	11.99	26	20	97	19.8		5.21	16.8	9.2	13.2	57	COM
008	724	23	95	5.76	-274	3.64	4.75	92	16.0	12.01	24	20	108	17.9		5.57	22.6	7.2	14.6	58	COM
009	729	16	96	5.95	-355	3.14	4.65	65	13.1	12.08	21	20	111	15.9		7.79	22.0	7.0	12.0	24	COM
010	729	17	108	5.98	-340	3.20	4.61	115	11.4	11.95	16	20	120	17.0		6.79	23.7	7.8	14.5	25	COM
011	729	18	115	5.91	-363	3.13	4.55	78	11.7	11.98	19	20	130	17.9		7.65	28.1	8.1	14.9	26	COM
012	729	19	98	6.15	-335	3.46	4.37	147	13.9	11.75	15	20	110	21.4		6.29	21.1	8.9	13.2	27	COM
013	729	20	101	6.09	-345	3.42	4.59	95	12.3	12.00	19	20	115	22.3		6.79	20.1	10.1	12.0	28	COM
014	729	21	88	6.10	-341	3.45	3.96	269	14.6	11.91	17	20	100	17.0		7.42	21.6	9.2	11.8	29	COM
015	729	22	104	6.16	-394	3.08	4.66	76	12.5	11.96	17	20	116	19.0		7.13	23.0	9.4	15.1	30	COM
016	807	15	94	5.82	-372	4.04	5.25	-79	11.0	11.92	19	20	111	23.2		6.08	14.5	11.3	14.4	14	COM
017	807	16	105	5.64	-358	4.38	4.72	51	15.9	11.89	17	20	124	19.7		7.25	16.8	11.3	15.1	15	COM
018	807	17	98	5.74	-386	4.38	5.16	21	16.3	11.95	15	20	115	20.5		7.09	15.9	11.2	15.1	16	COM
019	808	14	104	5.71	-360	5.55	5.44	-92	7.5	11.93	11	20	115	22.1		5.90	24.7	12.6	14.8	36	COM
020	808	15	108	5.70	-359	5.54	4.97	43	13.4	11.94	13	20	125	19.3		6.71	22.5	12.6	15.0	37	COM
021	808	16	81	5.69	-354	5.66	4.59	159	15.9	11.73	15	20	95	18.6		6.48	15.1	11.3	15.0	38	COM
022	808	17	68	5.72	-353	5.59	5.32	37	8.7	12.05	19	20	81	22.7		4.64	13.7	10.1	15.0	39	COM
023	808	18	77	6.08	-366	5.77	5.02	49	16.3	11.86	18	20	93	18.2		5.82	10.4	9.6	15.0	40	COM
024	808	19	112	6.01	-367	5.81	5.50	-53	7.4	12.04	12	20	127	18.6		6.45	22.7	9.8	16.4	41	COM
025	831	10	80	5.88	-291	4.41	4.88	-56	7.6	12.15	20	22	92	24.4	49.4	4.63	16.7	12.4	14.0	20	COM
026	831	19	71	6.02	-330	4.01	5.33	-134	10.1	12.10	20	22	80	23.0	49.6	4.05	13.7	12.0	9.5	29	COM
027	831	21	86	6.13	-343	3.67	5.35	-82	9.6	12.04	19	22	95	22.3	50.0	5.46	13.7	11.6	13.1	31	COM
028	901	23	78	5.92	-349	3.34	4.05	137	11.3	12.02	22	22	87	20.7	58.1	4.14	11.5	9.8	17.5	56	COM
029	902	8	70	5.75	-309	3.74	3.37	212	10.8	11.92	21	22	79	22.8	56.8	3.91	18.1	11.2	9.4	65	COM
030	902	11	80	5.91	-315	3.16	4.01	196	11.8	12.09	23	22	89	21.5	56.8	4.23	13.3	11.4	11.4	68	COM

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge				Cake			Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
031	902	12	79	5.72	-312	3.47	3.96	160	11.4	11.91	21	22	88	22.2	58.7	3.98	15.4	11.4	11.9	70	COM
032	902	13	78	5.69	-304	3.38	3.79	98	12.6	11.94	22	22	87	22.0	58.0	3.98	17.2	11.7	11.0	71	COM
033	902	21	75	6.06	-250	3.75	3.88	70	10.5	12.12	16	22	84	22.3	57.1	4.14	15.2	10.1	11.2	79	COM
034	903	17	86	5.95	-322	4.36	5.18	-27	7.1	12.06	20	22	100	23.8	47.1	5.17	17.8	15.1	17.9	94	COM
035	903	18	87	5.93	-326	4.18	5.23	-12	7.0	12.12	21	22	101	24.1	46.7	4.24	13.5	13.9	17.9	95	COM
036	903	20	88	5.87	-328	4.40	5.58	-122	6.4	11.61	19	22	102	23.0	48.1	5.11	17.9	14.9	17.9	97	COM
037	904	6	99	5.72	-342	4.45	5.31	-89	5.6	12.07	16	22	112	23.7	49.3	6.68	15.4	13.8	19.9	105	MAN
038	904	7	99	5.79	-341	4.60	5.24	-93	5.6	12.04	16	22	112	23.2	50.4	6.57	16.5	14.2	19.9	106	MAN
039	904	8	99	5.74	-339	4.61	5.38	-82	5.5	12.02	16	22	112	21.7	50.9	6.65	13.2	11.3	17.8	107	MAN
040	904	9	99	5.70	-338	4.47	5.47	-48	5.6	11.80	16	22	112	22.1	50.1	7.37	13.6	12.6	15.7	108	MAN
041	904	10	99	5.69	-340	4.59	5.34	-48	5.6	11.98	16	22	112	24.0	50.3	6.86	14.4	13.3	15.7	109	MAN
042	904	11	99	5.64	-337	4.43	5.37	-80	5.7	12.02	16	22	112	23.1	48.3	6.25	20.0	14.6	15.8	110	MAN
043	904	12	98	5.65	-336	4.31	5.34	-91	6.3	12.01	15	22	110	22.7	48.9	6.74	13.7	12.4	19.3	111	COM
044	904	13	112	5.64	-336	4.23	5.12	-5	8.8	11.84	14	22	126	21.0	50.4	7.75	11.9	10.6	22.1	112	COM
045	904	14	117	5.62	-336	4.52	5.19	-9	7.6	11.91	14	22	132	20.0	51.1	8.59	12.3	9.5	22.6	113	COM
046	904	15	119	5.61	-336	4.38	5.06	4	9.0	11.87	14	22	133	21.0	50.0	8.21	12.3	10.4	22.9	114	COM
047	904	16	104	5.58	-336	4.40	4.90	22	9.4	11.89	15	22	118	21.0	49.6	7.33	12.7	8.6	19.6	115	COM
048	904	17	93	5.57	-335	4.29	4.69	92	9.8	11.88	17	22	106	21.3	49.9	5.72	12.5	7.8	17.9	116	COM
049	904	22	93	5.65	-342	3.28	5.04	27	11.6	11.82	17	22	104	20.1	57.0	7.25	19.4	11.6	20.3	121	COM
050	904	23	109	5.63	-344	3.28	5.05	19	8.8	11.82	16	22	120	22.0	58.2	6.38	15.3	11.7	20.5	122	COM
051	911	9	85	5.26	-323	2.89	4.73	75	12.9	12.18	30	22	98	15.8	39.4	5.74	23.9	7.0	10.3	276	MAN
052	911	10	85	5.26	-324	3.02	4.40	103	12.0	12.17	29	22	98	15.4	40.3	5.47	26.2	7.4	10.3	277	MAN
053	911	12	85	5.29	-327	3.07	4.26	76	12.1	12.17	29	22	98	16.6	40.7	4.42	24.7	7.9	10.2	279	MAN
054	911	13	85	5.30	-328	3.00	4.36	69	12.3	12.16	29	22	98	16.2	39.4	5.21	25.3	7.9	10.4	280	MAN
055	911	15	76	5.36	-332	2.78	4.48	134	18.9	11.99	27	22	87	17.8	43.6	4.31	24.9	8.0	10.3	282	MAN
056	911	17	83	5.43	-336	2.75	4.35	196	13.1	11.93	23	22	93	18.8	55.7	4.39	24.7	9.4	11.4	284	COM
057	911	18	86	5.47	-336	2.83	4.11	152	13.3	11.89	23	22	96	17.9	55.2	4.50	24.3	8.1	12.3	285	COM
058	911	19	101	5.60	-333	2.99	4.45	103	13.0	11.87	20	22	112	20.0	56.1	5.66	24.3	13.6	14.8	286	COM
059	911	20	102	5.64	-336	2.97	4.46	115	19.9	11.77	23	22	118	18.1	52.6	6.70	24.0	11.7	16.6	287	COM
060	911	21	90	5.57	-334	2.88	5.18	179	19.7	11.71	25	22	105	18.7	53.9	5.32	21.6	9.5	16.2	288	COM

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge				Cake			Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
061	911	22	99	5.50	-336	2.76	4.60	240	17.4	11.93	29	22	114	15.2	52.5	6.68	21.0	7.4	15.4	289	COM
062	911	23	109	5.46	-335	2.81	4.67	227	18.2	11.87	26	22	124	15.8	44.2	7.43	21.3	7.2	17.1	290	COM
063	911	24	109	5.48	-332	2.66	4.53	203	15.4	11.70	28	22	124	15.4	44.3	5.33	25.3	6.5	18.3	291	COM
064	912	1	112	5.52	-334	3.16	4.86	179	11.5	11.88	21	22	126	18.7	47.5	7.30	25.0	8.1	18.2	292	COM
065	912	2	118	5.57	-332	3.23	5.12	136	9.5	11.86	20	22	134	17.6	44.6	5.58	24.6	7.4	18.1	293	COM
066	912	8	83	5.49	-340	2.92	4.03	269	14.5	12.14	36	22	98	17.3	37.8	5.24	11.4	8.8	13.7	299	MAN
067	912	11	83	5.45	-337	3.41	4.84	105	10.7	12.13	34	22	99	19.1	34.0	5.07	26.0	7.2	13.4	302	MAN
068	912	15	98	5.54	-347	4.12	5.45	-45	7.4	12.19	34	22	114	23.9	34.9	5.71	18.4	11.3	18.7	306	MAN
069	912	17	97	5.53	-344	4.13	5.32	-59	7.5	12.13	24	22	113	22.5	45.0	5.33	18.7	12.7	18.6	308	MAN
070	912	18	98	5.53	-344	4.33	4.87	39	8.9	11.91	16	22	111	20.9	57.0	5.41	19.5	13.9	18.5	309	COM
071	912	19	95	5.58	-362	4.49	4.96	35	8.9	11.89	17	22	108	21.7	58.4	5.35	17.2	14.2	18.4	310	COM
072	912	20	92	5.55	-350	4.26	4.86	-42	9.3	11.89	19	22	105	21.2	58.9	4.72	15.8	13.6	17.4	311	COM
073	912	21	84	5.56	-354	4.58	4.35	68	10.7	11.88	19	22	9[illegible]	21.6	58.7	4.18	15.8	13.0	14.5	312	COM
074	912	22	76	5.56	-345	4.50	4.72	66	7.9	11.94	19	22	88	22.7	57.8	4.02	15.0	13.5	14.5	313	COM
075	912	23	75	5.57	-345	4.39	4.72	212	10.0	11.90	21	22	87	17.6	50.0	3.93	13.2	13.0	15.0	314	COM
076	912	24	78	5.58	-345	4.40	4.72	66	10.8	11.88	20	22	90	22.8	53.2	3.78	12.9	13.1	15.9	315	COM
077	913	1	83	5.63	-342	3.74	4.40	-79	13.8	11.52	23	22	97	22.3	55.4	3.91	12.9	11.8	19.1	316	COM
078	913	2	62	5.66	-344	3.70	4.48	103	17.5	11.51	22	22	77	22.1	53.2	3.56	15.7	10.0	17.3	317	COM
079	915	9	67	5.61	-347	4.67	5.50	-123	9.5	12.02	18	22	80	19.4	51.0	4.96	18.3	11.5	14.9	378	MAN
080	915	15	62	5.62	-357	4.49	5.41	-169	11.2	12.13	34	22	78	17.6	44.3	4.61	20.8	5.9	16.6	384	MAN
081	915	17	87	5.69	-344	3.52	4.58	15	9.7	11.95	18	22	99	21.5	56.9	5.45	17.1	10.3	16.9	386	COM
082	915	20	85	5.91	-344	3.65	4.42	135	15.9	11.88	20	22	99	21.3	54.4	7.11	20.3	6.8	9.4	389	COM
083	915	21	77	5.88	-356	3.73	4.81	129	12.5	11.98	19	22	89	22.6	59.4	4.35	23.0	9.2	13.6	390	COM
084	915	22	81	5.88	-360	3.67	4.80	210	13.4	11.93	18	22	93	19.3	53.9	4.41	22.9	11.4	13.6	391	COM
085	915	23	79	5.86	-348	3.54	4.81	200	9.6	11.94	16	22	89	21.4	56.4	3.91	22.9	12.4	13.8	392	COM
086	915	24	80	5.82	-341	3.56	4.76	146	14.9	11.88	18	22	92	21.7	57.0	4.17	20.2	10.5	14.8	393	COM
087	916	10	88	5.52	-341	3.71	4.71	66	10.4	11.76	13	22	100	22.1	57.1	4.84	19.3	10.7	19.1	401	COM
088	916	11	86	5.52	-343	3.82	4.53	31	7.9	11.88	11	22	98	21.4	58.2	5.45	19.3	10.9	19.1	402	COM
089	916	12	91	5.52	-342	3.92	4.25	78	8.8	11.83	11	22	103	21.1	56.8	5.85	19.3	11.0	19.1	403	COM
090	916	13	88	5.51	-341	3.83	4.30	81	9.4	11.62	11	22	101	20.9	54.8	5.70	19.1	11.2	19.2	404	COM

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge				Cake			Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
091	916	15	72	5.57	-336	3.89	3.62	204	14.9	12.17	23	22	88	20.8	47.6	4.64	24.6	8.9	17.6	406	MAN
092	916	17	92	5.55	-339	3.63	4.52	234	11.7	12.13	18	22	108	21.7	42.9	6.08	24.7	10.5	17.0	408	MAN
093	916	18	82	5.51	-340	3.63	4.64	123	8.9	12.01	16	22	95	21.2	53.5	4.81	26.9	11.4	15.7	409	COM
094	917	7	78	5.32	-345	3.24	4.86	84	8.4	12.07	19	22	86	22.1	51.9	4.12	25.9	12.5	14.1	418	COM
095	917	9	79	5.31	-351	3.30	4.81	73	8.4	12.03	19	22	87	21.4	52.7	4.18	26.0	13.4	14.8	420	COM
096	917	13	90	5.27	-347	3.27	4.94	188	11.0	11.99	19	22	103	19.6	53.2	5.32	23.0	8.7	17.0	424	COM
097	917	15	107	5.26	-352	3.69	5.07	88	9.9	11.89	15	22	120	20.3	55.0	6.67	23.3	9.3	21.0	426	COM
098	917	16	113	5.87	-345	3.73	5.09	86	10.2	11.89	15	22	128	19.6	54.0	6.90	23.3	9.0	21.8	427	COM
099	918	16	97	5.55	-308	3.92	4.79	127	9.0	12.08	20	22	111	18.4	48.7	5.74	24.2	7.5	14.7	450	MAN
100	918	18	106	5.50	-310	3.84	4.50	132	12.7	11.90	18	22	120	17.4	50.0	7.75	22.3	7.3	16.6	452	COM
101	918	20	118	5.72	-321	3.57	5.03	65	13.6	11.88	18	22	133	18.4	48.8	8.07	23.6	8.0	19.9	454	COM
102	923	8	101	5.93	-362	3.55	4.65	-29	9.5	12.24	22	22	113	20.9	46.9	6.97	27.0	11.9	16.0	465	MAN
103	923	10	102	6.03	-360	3.64	4.67	-14	9.9	12.21	21	22	116	22.1	47.9	6.24	27.3	14.6	16.0	467	MAN
104	923	11	102	6.05	-367	3.61	5.35	20	10.3	12.21	21	22	116	21.6	48.4	6.48	27.3	15.5	16.0	468	MAN
105	923	12	103	6.01	-371	3.53	5.28	27	10.6	12.09	21	22	117	21.3	49.2	6.36	26.6	15.4	16.0	469	MAN
106	923	13	103	6.03	-369	3.60	4.70	54	10.3	12.14	21	22	117	22.1	46.2	6.57	26.8	15.4	16.0	470	MAN
107	923	14	104	6.07	-371	3.72	5.17	08	9.9	12.13	20	22	118	22.2	42.3	7.38	27.7	16.3	16.0	471	MAN
108	923	15	105	6.03	-372	3.59	4.82	00	10.2	12.13	20	22	118	21.9	44.4	7.04	26.4	15.0	16.0	472	MAN
109	923	16	104	5.96	-372	3.68	3.67	189	9.9	12.12	20	22	118	20.9	46.6	7.31	23.3	13.9	16.4	474	MAN
110	923	17	105	5.93	-373	3.69	3.55	249	9.9	12.12	20	22	119	22.2	45.7	6.87	20.7	13.7	16.4	475	MAN
111	924	9	103	6.24	-353	4.22	5.60	-64	6.5	12.20	21	22	119	22.4	38.1	6.25	19.0	10.9	21.0	491	MAN
112	924	10	103	6.25	-358	4.62	5.87	-81	6.0	12.20	19	22	119	24.8	42.5	6.07	20.3	11.5	21.0	492	MAN
113	924	11	105	6.48	-358	4.54	5.79	-131	6.0	12.18	19	22	121	25.4	42.3	6.01	18.8	11.7	21.0	493	MAN
114	924	16	97	6.39	-357	3.97	5.44	-177	10.2	11.91	17	22	108	21.3	51.0	5.88	19.6	10.6	17.1	498	COM
115	925	9	89	6.42	-343	3.60	5.48	-36	11.5	12.15	30	22	103	18.4	36.1	6.98	22.5	8.0	14.3	518	MAN
116	925	11	98	6.38	-341	2.82	5.24	38	13.2	12.15	34	22	112	21.1	38.0	6.22	21.5	10.2	14.3	520	MAN
117	925	15	91	6.35	-352	2.82	4.66	85	16.1	12.09	32	22	104	20.4	39.0	4.82	27.9	11.7	14.8	524	MAN
118	926	15	89	6.06	-326	3.91	5.31	319	13.4	12.12	27	22	104	19.9	43.1	5.36	16.2	12.9	15.2	16	MAN
119	930	10	98	5.74	-342	3.63	5.03	167	9.4	12.16	28	22	114	21.9	32.0	5.81	15.7	9.1	17.7	94	MAN
120	930	13	95	5.78	-348	3.76	4.22	222	9.3	12.04	29	22	107	20.8	36.8	5.67	19.6	11.2	18.2	97	MAN

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge				Cake			Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
121	1002	18	106	5.88	-337	3.02	5.31	-84	11.9	12.09	24	22	120	21.3	57.0	6.05	21.4	10.4	17.4	2	COM
122	1003	8	92	6.52	-361	4.39	5.72	-142	9.6	12.01	17	22	105	23.0	45.7	5.34	21.7	12.4	16.1	16	COM
123	1003	11	95	6.59	-353	4.01	5.40	-83	16.9	11.61	19	22	110	22.2	50.2	5.33	19.6	10.8	18.3	19	COM
124	1003	14	82	6.39	-367	3.91	5.06	105	18.5	11.50	25	22	100	20.6	48.2	4.51	18.7	9.4	12.6	22	COM
125	1006	11	77	5.68	-370	3.54	4.18	61	11.6	12.11	26	22	92	22.5	46.4	3.93	22.6	13.5	15.1	87	MAN
126	1006	12	77	6.05	-379	3.46	4.03	80	12.7	12.12	26	22	92	22.4	45.4	4.55	16.4	9.7	15.1	88	MAN
127	1006	14	86	6.03	-373	3.42	4.54	-92	10.4	12.04	22	22	98	20.8	51.8	4.56	17.3	10.3	16.4	90	COM
128	1007	15	91	5.96	-342	2.49	4.50	107	12.8	12.10	24	22	103	22.5	52.9	3.70	19.6	15.8	14.8	114	COM
129	1007	17	93	5.87	-350	2.60	4.39	92	15.7	12.03	24	22	106	21.3	43.0	4.80	21.3	13.2	17.0	116	COM
130	1007	18	78	5.83	-352	2.60	4.26	119	14.2	12.07	23	22	89	21.7	46.2	3.58	18.1	10.4	15.6	117	COM
131	1009	17	91	5.76	-362	3.59	5.23	-40	8.5	12.09	23	22	104	22.3	47.0	5.01	27.0	14.7	17.1	7	MAN
132	1009	18	99	5.75	-361	3.16	5.01	-30	10.3	12.02	18	22	112	20.7	48.9	6.31	17.4	12.8	15.5	8	COM
133	1010	12	81	5.81	-333	3.44	5.21	-30	9.9	12.12	27	22	95	23.6	42.3	4.81	24.8	13.6	14.0	18	MAN
134	1010	13	79	5.78	-335	3.50	5.10	-26	9.3	12.11	28	22	93	23.8	40.0	4.94	25.9	15.0	15.9	19	MAN
135	1010	16	89	5.65	-338	3.61	4.89	183	13.1	11.92	18	22	103	20.4	53.1	5.43	18.6	13.2	14.0	22	COM
136	1011	10	72	5.52	-337	4.62	5.31	-77	6.3	11.24	19	22	83	22.4	40.7	2.61	31.4	12.3	13.1	41	MAN
137	1011	12	80	5.63	-335	5.14	5.31	-99	5.9	12.08	15	22	89	23.3	49.6	5.75	21.1	18.9	16.3	43	COM
138	1017	14	105	5.54	-338	3.45	5.13	35	12.4	12.06	25	22	119	20.4	50.2	6.26	21.3	16.1	17.8	174	COM
139	1017	15	102	5.51	-336	3.06	4.82	139	13.7	12.03	28	22	116	20.6	50.9	5.23	21.0	15.8	16.9	175	COM
140	1017	16	90	5.50	-335	2.98	4.67	177	15.2	11.97	26	22	101	19.5	55.5	5.81	21.1	15.2	12.5	176	COM
141	1021	14	94	5.76	-363	3.83	5.48	-103	9.1	12.20	24	23	109	21.0	46.3	6.03	27.6	17.7	17.0	14	MAN
142	1021	16	96	5.70	-360	4.30	5.49	-136	8.6	12.13	20	23	111	21.7	45.5	6.58	23.5	17.0	18.0	16	MAN
143	1021	17	102	5.69	-357	3.74	5.02	-140	12.3	12.02	20	23	117	21.3	56.4	6.41	16.1	15.9	18.4	17	COM
144	1022	11	126	5.86	-371	2.67	4.93	-65	11.4	11.84	17	23	137	21.0	57.0	4.69	19.4	15.8	21.1	35	COM
145	1022	14	100	5.78	-360	2.70	4.52	62	11.6	11.92	19	23	110	24.2	53.8	3.54	18.8	15.7	14.8	38	COM
146	1022	16	107	5.68	-328	2.76	4.33	184	13.7	11.86	18	23	117	19.9	54.5	5.06	16.6	15.4	16.6	40	COM
147	1023	9	119	5.94	-352	2.87	4.29	47	12.9	12.18	25	23	135	22.9	53.0	5.98	20.0	14.8	19.3	57	COM
148	1023	12	133	5.94	-366	2.31	4.42	171	14.9	11.90	18	23	145	20.8	58.2	4.56	21.0	15.2	19.3	60	COM
149	1024	9	98	5.75	-346	3.19	3.00	387	24.0	12.28	28	23	114	16.2	55.4	7.35	21.9	17.9	19.8	81	MAN
150	1024	11	74	5.77	-357	3.74	3.00	499	26.0	12.17	28	23	90	20.1	49.3	4.79	17.5	15.8	11.5	83	MAN

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge			Cake				Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
151	1024	13	87	5.74	-356	4.52	4.80	257	7.4	11.98	13	23	96	20.3	60.2	4.83	18.2	16.1	16.0	85	COM
152	1024	15	88	5.74	-350	4.06	4.78	214	7.7	12.02	14	23	97	20.5	56.6	4.50	21.8	16.3	16.4	87	COM
153	1028	10	107	5.96	-346	3.43	5.42	-11	10.9	12.20	23	24	123	21.4	56.1	5.42	16.6	16.2	17.5	79	MAN
154	1028	11	113	6.14	-347	3.37	4.66	38	10.5	12.11	22	24	128	21.1	50.9	5.51	18.1	16.2	17.6	80	MAN
155	1028	13	111	5.73	-340	3.67	4.81	37	8.2	11.87	19	24	125	22.3	54.7	5.46	20.5	16.6	19.1	82	COM
156	1028	15	108	5.88	-347	3.14	4.70	42	9.1	11.94	18	24	119	21.8	57.2	4.72	18.6	16.8	15.2	84	COM
157	1028	16	113	5.80	-350	3.27	4.81	90	8.5	11.89	16	24	124	21.1	59.2	5.04	20.3	16.8	17.6	85	COM
158	1029	9	113	5.81	-354	3.41	4.19	125	11.3	12.07	21	23	128	23.2	62.5	6.49	19.4	17.0	17.9	102	MAN
159	1029	11	118	5.79	-352	3.09	4.54	54	12.0	12.13	22	23	132	20.8	55.8	6.54	20.0	17.0	17.9	104	MAN
160	1029	13	114	6.06	-352	3.31	4.49	145	8.3	11.95	16	23	128	19.6	57.4	4.93	20.5	16.8	15.6	106	COM
161	1029	14	118	6.20	-356	3.35	4.22	131	9.1	11.91	16	23	130	20.8	56.1	6.24	18.6	16.9	16.0	107	COM
162	1029	15	107	6.19	-359	3.06	3.99	116	9.3	11.90	18	23	118	22.3	55.3	5.24	20.8	17.1	16.8	108	COM
163	1030	9	116	5.77	-345	3.10	4.59	84	13.4	12.20	25	23	132	20.5	49.0	6.12	22.4	16.3	19.0	12	MAN
164	1030	11	123	5.82	-348	3.67	4.81	-33	11.2	12.20	20	23	139	18.9	50.3	7.79	26.9	16.9	18.7	14	MAN
165	1030	15	97	5.90	-353	3.32	4.90	32	9.1	11.94	16	23	107	18.9	58.2	6.26	18.5	17.4	14.0	18	COM
166	1030	16	92	5.94	-357	3.92	4.89	-43	7.1	11.96	20	23	106	19.6	59.9	6.58	17.3	16.4	14.9	19	COM
167	1031	11	122	6.07	-359	3.64	4.82	-24	12.1	12.20	17	23	137	20.3	57.8	7.11	20.6	16.4	18.4	38	MAN
168	1031	12	120	6.03	-360	3.17	4.36	16	14.4	12.20	19	23	135	21.3	60.7	6.03	19.8	15.9	18.4	39	MAN
169	1031	13	121	6.01	-360	3.06	4.44	17	14.5	12.20	20	23	136	20.6	58.3	5.96	18.7	15.2	18.4	40	MAN
170	1104	11	105	5.98	-290	3.77	4.32	99	11.7	12.21	16	22	116	25.9	54.9	5.00	13.4	16.7	17.8	134	MAN
171	1104	14	104	6.11	-337	3.27	3.87	159	10.3	11.93	13	22	112	21.7	65.1	4.13	17.4	17.6	18.6	137	COM
172	1104	15	110	6.11	-351	3.00	3.95	130	10.7	11.91	13	22	118	20.1	66.5	4.04	18.6	17.8	18.6	138	COM
173	1110	14	78	6.04	-366	3.33	5.04	121	11.4	12.18	33	21	93	22.3	50.0	5.06	13.6	12.4	10.8	31	MAN
174	1110	16	79	5.85	-363	3.46	4.44	107	9.9	11.93	21	21	90	19.9	54.7	5.55	15.9	12.6	13.7	33	COM
175	1110	17	78	5.72	-361	3.63	4.40	164	10.7	11.89	22	20	90	19.4	59.7	5.07	17.4	12.8	13.8	34	COM
176	1114	9	91	5.83	-355	3.79	5.09	-122	12.4	12.20	27	21	107	21.6	48.0	6.98	22.5	9.8	18.4	9	MAN
177	1114	12	98	5.81	-349	3.35	4.57	65	8.1	11.85	15	20	107	20.7	58.6	4.95	16.4	9.5	16.3	12	COM
178	1114	15	95	5.66	-345	3.31	4.27	133	7.2	11.91	17	20	105	19.6	59.2	4.61	17.6	9.5	15.4	15	COM
179	1118	16	82	5.94	-348	4.57	4.12	312	16.6	12.22	24	21	98	20.9	48.2	6.30	16.7	10.0	10.2	39	MAN
180	1120	9	82	6.01	-350	3.26	5.01	10	12.4	12.16	39	21	99	20.4	44.4	5.37	16.1	6.1	13.5	53	MAN

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge				Cake			Filter			
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH
181	1120	11	88	6.07	-353	3.35	5.51	-25	10.8	12.20	36	21	105	22.4	44.8	5.78	12.3	11.4	13.5	55 MAN
182	1125	12	109	5.85	-330	4.42	5.28	-2	10.3	12.15	19	20	125	21.3	56.4	6.38	31.4	14.8	13.9	37 MAN
183	1125	13	113	5.74	-330	4.37	4.99	-3	10.2	12.15	18	20	129	19.6	59.5	6.48	26.6	14.3	13.9	38 MAN
184	1125	14	112	5.70	-332	4.36	4.78	-8	10.2	12.15	18	22	128	19.8	57.6	6.40	28.6	13.9	13.9	39 MAN
185	1125	15	112	5.72	-332	4.44	4.69	-18	10.9	12.06	18	20	127	20.5	57.4	6.64	28.2	17.1	14.0	40 MAN
186	1125	16	95	5.76	-332	4.51	4.02	226	8.1	11.98	16	19	109	18.6	59.4	5.82	21.9	15.6	15.3	41 COM
187	1125	17	92	5.74	-331	4.58	4.82	101	7.4	11.89	14	19	104	19.3	65.5	5.54	22.5	15.8	18.3	42 COM
188	1202	10	111	5.59	-382	3.50	4.23	34	11.5	12.20	23	21	128	19.4	52.6	5.22	24.7	18.3	17.0	17 MAN
189	1202	11	103	5.68	-336	3.21	4.40	11	13.4	12.20	28	21	120	18.6	55.1	5.42	27.3	18.6	18.2	18 MAN
190	1202	12	105	5.86	-336	3.36	4.51	-5	12.6	12.20	27	22	122	17.2	56.7	5.01	25.4	18.3	23.3	19 MAN
191	1202	14	92	5.88	-320	3.53	4.30	25	13.7	12.20	30	22	109	21.1	50.7	4.42	24.4	18.0	16.6	21 MAN
192	1202	15	110	5.91	-333	2.97	4.32	21	14.8	12.20	29	20	127	21.4	52.4	4.69	23.6	18.3	21.0	22 MAN
193	1202	17	100	5.89	-347	3.32	3.93	110	8.2	11.68	19	19	111	19.4	65.4	4.53	21.8	18.7	23.4	24 COM
194	1202	18	111	5.88	-354	3.26	4.29	82	8.1	11.91	22	19	126	19.1	64.5	5.16	21.1	17.9	22.7	25 COM
195	1205	8	76	5.93	-353	3.23	4.14	349	14.6	12.30	35	21	92	24.0	49.2	4.74	14.4	14.6	11.9	76 MAN
196	1205	9	80	5.96	-341	3.20	4.39	336	14.1	12.30	33	21	96	23.3	49.7	4.98	13.7	14.3	11.9	77 MAN
197	1205	10	78	5.90	-334	3.27	5.19	126	15.6	12.36	31	21	93	20.8	50.0	5.04	15.7	14.8	12.7	78 MAN
198	1205	11	89	5.92	-332	3.45	4.73	162	16.1	12.34	26	20	105	17.9	54.5	5.27	25.4	15.8	12.4	79 MAN
199	1205	12	98	5.92	-308	3.51	3.10	243	14.3	12.27	24	20	114	18.1	57.2	6.65	31.0	16.3	12.9	80 MAN
200	1205	15	109	5.93	-321	3.32	3.81	367	13.5	12.39	27	20	126	19.1	51.6	6.28	35.9	18.7	15.3	83 MAN
201	1209	10	104	5.75	-369	4.38	5.05	18	10.9	12.30	23	20	121	20.0	58.9	5.44	31.3	13.8	18.9	18 MAN
202	1209	11	88	5.90	-370	4.04	4.94	39	13.1	12.30	27	21	105	20.3	51.9	6.19	31.5	16.3	19.7	19 MAN
203	1209	13	94	6.04	-372	4.76	4.86	143	11.2	12.35	23	20	111	22.3	54.8	6.03	33.0	16.8	19.7	21 MAN
204	1209	14	77	6.05	-378	4.33	5.18	-3	8.4	12.11	20	20	92	20.8	62.6	5.15	28.8	17.1	20.2	22 COM
205	1209	15	73	5.80	-373	4.28	4.65	91	10.7	12.05	20	20	85	20.9	61.6	4.15	24.4	17.3	20.0	23 COM
206	1209	16	73	5.93	-379	3.89	4.24	198	12.1	12.02	21	20	84	22.5	60.9	4.10	24.9	17.2	14.8	24 COM
207	1210	9	88	6.00	-357	3.59	3.73	261	18.2	12.30	31	21	106	23.4	53.4	4.92	26.4	16.7	19.7	41 MAN
208	1210	15	86	5.82	-359	3.82	3.00	272	12.3	12.30	30	21	104	17.8	55.5	4.40	37.2	17.8	13.9	47 MAN
209	1210	16	66	5.84	-358	3.91	3.75	253	11.3	12.09	23	20	80	20.4	58.8	3.41	23.6	22.1	14.1	48 COM
210	1210	17	60	5.77	-357	3.91	3.49	406	8.7	11.98	23	20	73	22.2	61.2	3.11	27.1	18.1	14.7	49 COM

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge				Cake			Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
211	1211	17	103	6.32	-355	3.65	3.92	313	13.8	12.05	25	21	119	18.2	62.3	5.95	24.2	15.7	18.4	13	MAN
212	1212	12	106	5.87	-348	3.09	4.03	323	15.6	12.15	28	21	123	21.4	61.0	5.40	19.8	13.6	21.8	30	MAN
213	220	9	88	6.25	-406	4.40	5.01	32	7.6	12.19	25		105	22.8	54.5	6.01	8.1	15.8	16.5	84	MAN
214	220	11	100	6.43	-417	4.01	5.40	-123	7.4	12.11	23		117	22.3	53.3	5.89	13.5	17.9	16.5	86	MAN
215	220	12	97	6.59	-401	4.19	5.39	-122	9.0	11.96	18		109	20.7	63.8	5.67	13.7	18.4	16.5	87	COM
216	220	13	103	6.53	-393	4.20	5.14	-59	9.7	11.90	18		116	21.3	60.7	6.36	12.4	17.8	17.0	88	COM
217	302	13	103	6.21	-384	3.24	3.33	311	9.7	12.16	22		114	23.6	54.5	4.64	13.3	18.9	14.8	148	MAN
218	302	15	99	6.21	-385	3.12	4.36	139	8.1	12.27	17		107	23.2	59.2	4.15	10.9	17.3	16.9	150	COM
219	302	16	99	6.20	-382	3.14	4.52	135	8.4	12.28	17		107	23.3	60.7	4.09	13.6	19.2	17.0	151	COM
220	304	15	96	6.34	-396	3.86	5.31	-21	9.2	12.31	24		107	21.1	48.9	6.05	12.4	15.6	11.0	197	MAN
221	304	17	93	6.31	-400	4.04	5.40	-78	9.6	12.25	15		102	20.6	55.6	5.56	12.8	17.1	14.4	199	COM
222	318	10	68	6.65	-358	5.90	5.73	-190	7.8	12.32	23		81	23.6	47.3	5.53	8.9	18.3	12.4	42	MAN
223	318	11	71	6.78	-380	5.91	5.52	-190	8.9	12.24	21		84	23.5	49.7	5.51	10.4	18.1	12.3	43	MAN
224	318	14	73	6.55	-366	5.44	5.30	-158	9.1	12.21	15		82	21.0	56.4	4.79	9.6	17.9	11.8	46	COM
225	318	15	75	6.55	-359	5.67	5.42	-157	8.3	12.24	14		84	21.0	57.7	4.88	11.9	18.9	11.9	47	COM
226	318	16	77	6.52	-340	5.74	5.41	-160	8.1	12.23	14		86	21.2	60.2	5.40	12.1	19.5	12.7	48	COM
227	406	16	84	6.14	-373	4.80	5.10	128	6.2	12.19	13		93	21.5	61.7	5.41	14.3	17.8	15.8	4	COM
228	406	19	82	6.37	-387	3.60	5.14	184	10.8	12.16	24		94	20.6	58.8	5.32	13.9	14.1	12.7	7	MAN
229	406	20	89	6.09	-379	4.30	5.12	64	7.8	12.24	14		98	22.7	56.5	5.58	13.3	16.9	13.2	8	COM
230	406	21	100	6.33	-379	3.50	5.11	160	10.7	12.03	16		110	19.8	61.1	6.10	13.6	17.5	14.7	9	COM
231	406	22	90	6.40	-384	3.30	5.56	62	10.2	12.24	18		100	19.7	58.8	5.65	13.3	17.5	12.7	10	COM
232	406	23	93	6.20	-377	3.90	5.32	61	8.1	12.24	15		103	20.5	58.7	5.49	13.5	17.6	13.4	11	COM
233	406	24	88	6.10	-369	4.00	5.06	166	7.4	12.26	15		97	22.5	56.5	5.16	13.1	17.6	13.0	12	COM
234	407	01	95	6.26	-372	3.10	5.34	115	10.7	12.20	18		105	20.5	57.8	5.39	11.8	17.6	14.8	13	COM
235	407	2	97	6.17	-370	3.40	5.05	147	9.3	12.19	16		106	21.0	59.8	5.51	12.3	17.5	14.8	14	COM
236	407	3	100	6.04	-364	3.60	4.42	239	9.9	12.16	15		111	20.4	61.3	5.40	12.1	17.7	14.7	15	COM
237	407	4	100	6.01	-362	3.10	4.10	297	10.2	11.96	18		111	21.4	61.6	5.23	12.0	17.7	14.6	16	COM
238	407	5	106	6.00	-363	3.40	4.08	332	10.4	12.16	21		116	21.2	58.7	4.51	11.7	17.7	16.6	17	COM
239	407	6	96	5.96	-362	3.30	4.69	241	8.4	11.99	17		106	21.2	57.7	4.07	13.7	17.7	16.1	18	COM
240	407	7	89	5.94	-365	3.40	4.47	327	9.2	12.15	24		102	22.7	50.8	5.17	11.6	17.7	12.0	19	MAN

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge				Cake			Filter			
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH
241	407	8	109	5.98	-364	2.60	4.67	259	9.0	11.87	15		118	20.3	62.6	4.12	15.8	17.7	16.5	20 COM
242	407	9	110	5.97	-363	2.60	4.96	202	9.0	12.01	17		120	21.8	60.5	3.98	18.6	17.7	16.4	21 COM
243	407	10	95	6.06	-365	3.80	5.59	136	10.9	12.00	14		105	21.6	62.3	5.56	15.7	17.8	14.2	22 COM
244	407	11	98	6.03	-365	2.80	4.53	199	13.6	11.87	20		108	20.5	60.5	4.64	16.6	17.8	15.5	23 COM
245	407	12	107	6.00	-358	2.60	4.18	274	14.2	11.91	22		119	20.3	60.4	4.11	17.4	17.8	15.3	24 COM
246	407	15	82	6.02	-363	2.50	4.56	56	9.2	12.21	29		92	23.1	49.7	3.57	17.2	18.4	11.4	25 MAN
247	407	17	94	6.13	-367	2.80	4.68	124	12.7	12.21	20		104	20.5	56.6	4.23	13.7	18.0	12.3	27 COM
248	407	18	94	6.16	-369	3.30	4.86	116	11.3	12.21	17		104	19.5	55.7	5.45	12.2	18.2	12.5	28 COM
249	407	19	98	6.08	-365	3.60	4.98	92	9.2	12.24	15		108	20.7	57.8	5.64	13.8	18.2	14.7	29 COM
250	407	20	94	6.06	-364	3.60	5.05	76	9.0	12.26	16		104	21.4	57.2	5.14	13.6	18.3	14.6	30 COM
251	407	21	96	6.06	-364	3.70	5.02	110	8.4	12.25	16		106	21.4	57.6	5.16	13.9	18.3	15.8	31 COM
252	407	22	95	6.09	-364	3.70	5.09	97	9.6	12.26	16		105	21.4	60.2	5.24	13.2	18.3	15.2	32 COM
253	407	23	83	6.15	-369	3.60	5.08	10	10.1	12.26	18		103	19.8	56.0	5.53	11.2	18.2	12.7	33 COM
254	407	24	94	6.06	-364	3.80	4.74	45	9.3	12.22	15		104	21.2	60.4	4.93	13.3	18.3	14.9	34 COM
255	408	1	91	6.10	-363	3.70	5.01	112	8.1	12.07	17		101	20.4	63.9	4.72	14.6	18.5	15.4	35 COM
256	408	2	70	6.06	-361	3.60	4.79	68	8.0	12.16	22		79	22.3	61.1	3.79	13.0	18.5	12.2	36 COM
257	408	3	87	6.16	-370	3.80	5.01	46	11.0	11.96	17		99	21.2	62.6	4.66	12.2	18.5	15.9	37 COM
258	408	4	80	6.19	-371	3.70	5.07	5	12.7	12.05	25		93	21.1	57.6	5.09	13.5	18.3	14.1	38 COM
259	408	5	86	6.08	-367	4.20	4.44	337	11.0	11.95	21		99	21.5	60.5	5.25	11.2	18.4	12.7	39 COM
260	408	6	82	6.06	-364	4.60	4.53	314	9.8	11.90	18		94	21.3	62.9	4.64	12.5	18.4	12.9	40 COM
261	408	7	82	6.07	-364	4.60	4.45	291	9.2	11.95	17		93	21.2	64.8	4.74	12.2	18.4	12.5	41 COM
262	408	8	83	6.07	-360	4.20	4.56	178	9.4	11.90	16		93	21.0	62.2	4.66	13.1	18.4	13.9	42 COM
263	408	9	83	6.11	-376	4.80	5.00	77	10.0	11.91	14		94	23.0	57.1	5.18	12.9	18.3	13.8	43 COM
264	408	10	87	6.19	-382	4.60	5.51	14	10.8	11.94	14		98	23.7	58.7	5.93	10.8	18.2	13.0	44 COM
265	408	14	103	6.22	-373	3.60	5.43	1	9.9	12.03	15		113	22.3	62.2	5.45	14.5	17.7	15.5	46 COM
266	408	15	101	6.13	-369	4.00	5.53	16	10.1	11.99	14		112	21.1	62.8	5.69	15.0	17.6	16.5	47 COM
267	408	16	98	6.14	-368	4.00	5.39	86	9.0	11.95	14		108	21.2	60.3	5.58	14.1	17.6	14.8	48 COM
268	408	17	93	6.12	-366	4.10	5.48	-12	8.4	12.08	14		103	20.8	62.4	5.33	15.1	17.7	15.7	49 COM
269	408	18	94	6.08	-364	4.30	5.45	14	8.0	12.08	14		104	21.3	64.0	5.43	14.8	17.6	15.4	50 COM
270	408	19	95	6.08	-361	4.10	5.39	58	8.0	12.09	14		105	20.9	63.2	5.40	15.6	17.7	16.1	51 COM

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

			Raw Sludge				FeCl3 Sludge			CaO Sludge			Cake				Filter				
LINE	DATE 80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
271	408	20	98	6.28	-364	3.10	5.60	107	9.9	12.13	18		108	19.6	60.2	5.06	14.7	17.7	14.4	52	COM
272	408	21	94	6.40	-371	3.10	5.35	-68	10.0	12.24	18		104	23.3	59.9	4.94	14.8	17.8	14.4	53	COM
273	408	22	97	6.19	-382	3.50	5.51	-94	9.4	11.94	17		107	19.1	63.6	5.53	10.8	18.2	13.0	54	COM
274	408	23	97	6.37	-375	3.30	5.40	-20	10.2	12.18	18		107	20.0	61.0	5.20	15.6	18.6	16.1	55	COM
275	409	1	99	6.31	-373	3.10	4.88	151	10.2	12.15	18		109	20.4	62.3	4.57	14.2	18.5	15.2	57	COM
276	409	2	106	6.30	-377	2.70	4.80	230	11.7	12.15	19		116	20.5	61.4	4.58	14.4	18.5	15.4	58	COM
277	409	3	110	6.31	-376	2.40	4.42	324	11.3	12.18	22		120	22.0	60.8	4.16	18.2	18.5	16.2	59	COM
278	409	4	111	6.35	-375	2.40	4.51	210	11.8	12.05	21		121	21.6	61.8	4.50	18.7	18.6	15.0	60	COM
279	409	5	111	6.37	-381	2.60	4.57	98	13.0	12.07	19		121	20.5	64.4	4.97	15.8	18.3	15.1	61	COM
280	409	6	107	6.37	-386	2.80	4.59	41	12.0	11.96	19		118	21.3	63.7	5.27	14.1	18.5	15.2	62	COM
281	409	8	105	6.33	-381	2.80	4.63	-1	12.0	12.08	19		115	20.6	63.3	4.51	13.4	18.5	14.3	64	COM
282	409	9	115	6.32	-380	2.50	4.59	132	12.0	12.08	19		126	23.3	61.0	4.31	14.8	18.4	15.6	65	COM
283	409	10	129	6.36	-383	2.20	4.53	176	13.0	12.02	20		140	22.8	62.0	4.33	15.7	18.4	17.1	66	COM
284	409	11	116	6.34	-382	2.50	4.77	224	13.0	12.05	19		127	23.0	60.5	4.31	15.3	18.3	16.9	67	COM
285	609	18	60	5.56	-313	4.40	5.33	-107	12.0	11.83	19		69	20.4	57.9	4.58	18.7	12.9	12.1	72	COM
286	609	19	58	5.57	-314	4.50	5.27	-18	13.0	11.90	24		69	19.8	55.3	4.75	18.5	7.4	12.4	73	COM
287	609	20	72	5.54	-319	4.70	5.39	-47	12.0	11.94	20		84	19.6	56.0	5.84	13.6	11.5	13.8	74	COM
288	609	21	69	5.50	-323	4.70	5.26	-14	11.0	11.93	20		81	21.4	58.3	5.73	15.4	10.9	12.9	75	COM
289	609	22	70	5.50	-332	4.80	5.26	-50	10.0	11.85	20		82	18.8	57.8	5.80	15.6	11.3	14.6	76	COM
290	609	23	73	5.54	-329	4.70	5.32	-61	12.0	11.92	20		85	18.6	57.2	6.41	15.5	9.8	14.3	77	COM
291	610	2	59	5.57	-330	4.60	5.38	-16	13.0	11.87	23		70	20.0	58.1	5.18	16.8	7.7	14.6	80	COM
292	610	3	59	5.56	-330	4.60	5.32	16	9.8	11.97	23		70	19.6	49.4	4.87	14.1	9.6	13.7	81	COM
293	610	4	64	5.57	-331	4.60	5.34	-29	14.0	11.88	17		74	17.7	59.4	5.62	13.8	11.7	13.0	82	COM
294	610	5	66	5.59	-330	4.70	5.32	14	14.7	11.85	19		77	19.5	57.3	5.75	14.0	12.1	13.0	83	COM
295	610	6	57	5.59	-333	4.60	5.20	59	13.0	12.06	19		66	16.3	51.7	6.10	19.1	6.0	11.6	84	COM
296	610	7	63	5.60	-333	4.60	5.33	-14	11.0	12.09	17		72	18.4	55.4	6.00	13.7	11.4	13.1	85	COM
297	610	8	65	5.60	-338	4.60	5.23	-24	12.0	12.07	16		75	18.4	57.0	5.95	13.4	10.9	13.1	86	COM
298	610	9	66	5.58	-337	4.60	5.33	-40	12.0	12.05	16		76	19.7	59.4	5.93	13.8	11.2	13.0	87	COM
299	610	10	79	5.50	-369	4.80	5.25	-24	9.9	11.79	15		89	19.1	56.7	5.28	17.3	10.6	13.2	88	COM
300	610	14	58	5.51	-304	4.20	5.35	-45	13.0	12.10	26		69	19.0	47.2	4.82	16.5	11.0	14.3	92	MAN

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge			Cake				Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
301	610	15	68	5.51	-304	4.40	5.26	-33	10.0	12.11	18		78	19.5	52.6	5.75	13.4	13.3	15.0	93	COM
302	610	16	68	5.51	-304	4.30	5.30	-22	10.0	12.05	17		77	18.6	56.5	4.86	14.4	13.5	16.9	94	COM
303	610	17	60	5.51	-307	4.30	5.24	54	11.0	12.05	19		69	18.6	55.1	4.66	15.9	12.2	14.1	95	COM
304	610	18	59	5.57	-307	4.00	5.09	-4	11.0	12.07	23		70	18.3	56.0	5.26	15.8	12.2	14.4	96	COM
305	610	19	60	5.62	-311	4.20	5.24	-8	13.0	12.02	20		69	18.2	55.2	4.94	14.3	9.7	14.0	97	COM
306	610	20	63	5.56	-311	4.20	5.17	-34	13.0	11.90	18		73	16.8	55.1	5.79	14.0	8.5	12.8	98	COM
307	610	21	68	5.62	-310	4.50	5.34	-37	15.0	11.87	18		79	18.5	56.3	6.07	13.6	10.0	14.0	99	COM
308	610	22	66	5.62	-316	4.50	5.24	22	15.7	11.92	20		77	19.5	52.3	6.14	14.6	12.7	12.4	100	COM
309	610	23	63	5.53	-312	4.30	5.27	21	15.8	11.87	18		73	16.6	54.4	5.88	13.8	8.6	12.2	101	COM
310	610	24	64	5.51	-313	4.30	5.23	-6	14.0	12.04	18		73	18.3	56.2	6.09	13.7	8.6	12.6	102	COM
311	611	1	63	5.52	-311	4.20	5.25	-25	13.0	12.04	18		72	18.5	56.2	5.57	13.4	11.9	13.3	103	COM
312	611	2	67	5.60	-314	4.20	5.37	-46	14.0	12.06	18		76	18.2	59.7	5.80	13.7	12.2	14.6	104	COM
313	611	3	65	5.52	-315	4.30	5.31	-37	14.0	12.08	18		74	18.6	58.4	5.52	14.3	12.5	15.0	105	COM
314	611	4	66	5.50	-316	4.30	5.29	-22	13.0	12.11	17		75	18.0	59.0	5.12	13.4	11.7	14.6	106	COM
315	611	5	66	5.57	-313	4.50	5.34	-18	13.0	11.95	16		75	18.3	56.0	5.62	13.9	12.6	16.4	107	COM
316	611	6	65	5.51	-313	4.40	5.31	-10	14.0	11.92	17		74	18.2	58.1	5.18	14.1	12.5	15.5	108	COM
317	611	7	65	5.51	-314	4.30	5.28	-25	12.0	12.11	18		74	18.8	56.7	5.08	13.7	12.5	14.8	109	COM
318	611	8	65	5.60	-316	4.40	5.28	-6	12.0	12.01	17		74	19.5	57.7	5.18	13.9	11.7	15.6	110	COM
319	611	20	61	5.73	-320	4.50	5.57	-34	14.0	11.88	20		71	19.9	55.8	6.88	15.4	13.5	10.8	113	COM
320	611	23	56	5.61	-318	4.40	5.43	-40	16.0	12.02	25		66	18.0	42.5	5.85	17.6	8.7	11.2	116	MAN
321	611	24	58	5.57	-317	4.40	5.48	-38	15.0	12.11	23		68	17.9	49.4	6.36	16.1	7.2	11.2	117	MAN
322	612	3	51	5.56	-319	4.30	5.37	-33	15.0	12.11	22		59	18.5	50.0	6.00	15.7	7.6	9.2	120	MAN
323	612	4	49	5.51	-316	4.30	5.32	-25	13.0	12.05	22		57	18.4	49.4	5.62	15.6	7.9	9.2	121	MAN
324	612	5	46	5.51	-319	4.30	5.38	-32	12.0	12.09	22		53	18.7	52.4	4.84	15.6	8.9	9.1	122	MAN
325	612	6	47	5.51	-319	4.30	5.41	-45	14.0	12.06	22		54	17.0	53.3	5.92	17.1	7.9	9.1	123	MAN
326	612	7	47	5.54	-318	4.30	5.32	-10	14.0	12.03	21		55	18.3	48.0	6.29	20.1	8.4	9.1	124	MAN
327	612	8	59	5.60	-318	4.50	5.37	-60	13.0	11.98	21		66	19.9	54.9	6.50	15.3	10.6	10.6	125	MAN
328	612	9	57	5.70	-319	4.90	5.37	-15	13.0	11.95	20		65	16.5	50.9	7.12	15.3	12.1	9.4	126	MAN
329	624	10	66	5.83	-382	4.10	5.39	-4	12.0	11.93	23		78	21.6	53.8	4.70	15.9	11.8	10.0	33	MAN
330	624	11	64	5.82	-389	4.10	5.41	13	12.0	11.73	19		74	20.2	54.5	4.85	14.7	11.4	10.3	34	COM

TABLE B1. COMPLETE DATA SETS FOR FILTER NO. 1

	DATE		Raw Sludge				FeCl3 Sludge			CaO Sludge			Cake				Filter				
LINE	80/81	HR	Q	PHR	ORPR	SSR	PHF	ORPF	PF	PHL	PL	TEMP	Q	TS	TVS	TPH	VAT	VAC	RPH	CLOTH	
331	624	12	71	5.82	-412	4.00	5.54	-57	11.0	11.88	18		81	20.2	53.1	5.85	15.5	11.7	10.5	35	COM
332	624	13	67	5.82	-408	4.20	5.67	-83	11.0	11.90	18		77	20.5	61.4	6.03	15.6	11.7	11.2	36	COM
333	624	14	67	5.83	-395	4.10	5.48	-12	11.0	11.94	19		78	19.8	54.2	5.72	13.5	11.3	13.8	37	COM
334	624	15	64	5.84	-399	4.10	5.53	16	10.0	11.85	18		74	21.5	53.7	5.27	15.0	11.0	16.2	38	COM
335	624	16	64	5.87	-403	4.20	5.42	69	10.0	11.55	17		73	21.0	51.4	4.39	15.5	12.0	15.9	39	COM
336	624	17	72	5.87	-396	4.40	5.51	44	10.0	11.62	16		82	22.0	53.4	5.28	15.1	12.0	16.9	40	COM
337	624	18	76	5.88	-403	4.40	5.53	35	11.0	11.85	17		87	20.9	56.2	5.70	15.4	11.4	16.9	41	COM
338	624	19	70	5.84	-400	3.90	5.57	53	11.0	11.77	19		80	20.8	54.7	4.01	19.4	9.6	12.4	42	COM
339	624	20	78	5.87	-403	4.00	5.42	69	9.2	11.55	21		87	19.2	53.9	5.02	15.5	12.0	15.9	43	COM

TABLE B2. COMPLETE DATA SETS FOR FILTER NO. 2

	DATE		Sludges					Cake			Filter		
LINE	80/81	HOUR	Q	SSR	PF	PL	Q	TS	TVS	TPH	VAT	VAC	RPH
1	901	23	76	3.6	10.0	34	90	20.1	55.1	4.8	12.3	10.3	16.3
2	902	8	81	3.8	9.1	30	95	21.1	54.1	4.3	10.0	10.8	16.3
3	902	11	81	2.6	13.2	43	95	22.1	55.6	4.2	11.2	10.7	16.5
4	902	12	86	3.5	9.3	31	100	21.4	57.0	4.3	12.8	10.6	17.7
5	902	13	87	3.3	9.8	32	101	21.4	57.0	4.3	15.2	10.6	17.7
6	902	21	83	3.8	8.6	25	97	21.6	55.9	4.5	11.2	10.3	18.0
7	904	17	71	4.3	8.4	26	85	21.2	44.4	5.2	24.1	14.0	16.4
8	904	22	63	3.1	12.8	39	77	22.6	46.9	4.1	13.7	12.9	17.5
9	904	23	64	3.3	12.3	37	78	22.1	45.7	4.1	12.3	13.4	17.5
10	911	9	56	2.5	20.0	56	70	17.7	38.9	4.2	20.2	6.9	13.4
11	911	10	55	2.8	19.0	41	69	17.2	36.9	4.3	18.9	6.7	13.4
12	911	12	52	2.9	17.5	51	66	17.7	37.8	4.7	17.9	7.8	12.8
13	911	13	55	2.9	17.0	40	69	18.1	36.1	4.5	18.5	7.3	12.8
14	911	15	52	2.5	22.5	49	66	18.0	36.7	3.8	17.7	6.6	12.8
15	911	17	63	2.5	19.0	50	77	18.0	47.2	4.7	18.7	9.0	13.6
16	911	18	63	2.6	19.0	47	77	17.8	46.5	4.8	20.2	8.7	13.8
17	911	19	63	2.8	18.0	45	77	20.8	44.2	5.0	20.9	13.1	13.8
18	911	20	62	2.8	19.0	46	76	20.2	41.9	4.8	20.8	12.7	13.8
19	911	21	66	2.4	20.0	50	80	20.3	42.8	5.0	19.0	11.4	13.8
20	911	22	63	2.2	24.0	60	77	18.3	42.9	5.3	23.9	8.9	13.7
21	911	23	60	2.5	21.0	52	74	17.9	34.9	4.9	21.3	7.6	12.8
22	911	24	52	2.3	27.0	66	66	17.1	33.4	4.0	21.1	5.3	12.8
23	912	1	53	3.1	18.0	48	67	18.7	34.7	5.3	25.0	7.2	12.8
24	912	8	80	3.0	14.0	33	94	19.2	39.2	5.8	25.5	10.7	16.1
25	912	17	72	3.8	12.0	28	86	19.9	47.4	4.7	21.6	6.4	16.5
26	912	18	77	4.1	11.0	25	91	23.1	54.4	5.8	17.9	14.3	16.5
27	912	19	75	4.2	11.0	25	89	21.5	46.8	5.8	25.9	14.7	16.5
28	912	20	75	4.0	11.0	26	89	21.6	45.7	5.8	20.1	14.1	16.5
29	912	21	76	4.2	10.3	25	90	21.6	44.4	6.0	16.6	13.6	16.5
30	912	22	75	4.4	10.1	24	89	21.7	47.4	5.5	32.3	14.0	16.5
31	912	23	80	4.4	9.4	22	94	18.1	34.5	5.6	22.5	13.9	16.5
32	912	24	80	4.5	9.2	22	94	21.9	47.8	5.7	18.8	13.7	16.5
33	913	1	83	3.8	10.2	24	97	19.9	46.5	5.7	23.7	12.9	16.5
34	913	2	84	3.8	9.8	24	98	19.8	47.9	5.8	26.5	12.9	16.5
35	915	15	57	3.8	18.0	36	71	19.6	34.0	4.6	16.8	6.8	12.5
36	915	17	60	3.5	22.0	31	75	21.9	35.8	4.4	13.7	11.3	12.6
37	915	20	55	3.8	22.0	30	70	23.1	37.8	3.8	13.4	7.8	13.0
38	915	21	60	3.9	20.0	28	75	22.9	35.9	4.1	16.9	10.8	13.0
39	915	22	63	3.9	19.0	26	78	24.4	34.4	4.2	13.0	12.8	13.0
40	915	23	62	3.8	19.0	27	77	24.1	36.7	4.2	12.5	13.0	13.0

TABLE B2. COMPLETE DATA SETS FOR FILTER NO. 2

			Sludges					Cake			Filter		
LINE	DATE 80/81	HOUR	Q	SSR	PF	PL	Q	TS	TVS	TPH	VAT	VAC	RPH
41	915	24	60	3.8	20.0	28	75	23.3	36.6	4.2	12.7	11.5	13.0
42	916	10	63	3.7	18.5	22	78	22.4	41.8	4.4	15.6	10.9	14.6
43	916	11	64	4.1	17.0	19	79	22.0	42.0	4.2	15.4	10.9	14.6
44	916	12	65	4.1	16.0	19	80	21.8	40.1	4.1	14.5	11.0	14.6
45	916	13	72	4.0	15.0	19	87	21.6	42.2	4.6	15.6	11.4	14.6
46	916	14	64	3.9	17.5	21	79	22.1	43.5	3.7	23.0	10.5	14.6
47	916	17	75	3.6	17.0	19	89	20.5	41.9	4.3	25.2	10.9	11.7
48	916	18	73	3.6	17.0	20	87	22.1	40.3	4.7	21.4	14.1	13.9
49	917	13	70	3.2	17.0	36	84	21.2	41.1	4.0	19.5	12.5	14.7
50	917	15	69	3.6	15.0	26	83	21.1	45.0	4.0	15.6	12.6	14.7
51	917	17	68	3.8	15.0	25	82	21.4	43.7	4.2	16.2	12.9	14.7
52	918	18	82	4.0	13.0	24	97	19.1	46.1	5.5	25.2	10.6	15.3
53	918	20	87	3.8	12.5	23	102	18.7	45.9	5.3	27.7	11.6	16.2
54	924	9	84	4.4	12.0	30	98	20.1	52.8	5.1	20.1	13.9	15.9
55	924	10	81	4.4	11.5	29	95	21.2	46.1	5.6	25.3	14.8	15.9
56	924	11	88	4.4	11.0	25	102	23.0	52.5	6.1	23.3	14.5	15.9
57	924	16	83	4.1	11.5	27	97	20.3	48.5	5.8	21.8	13.5	15.9
58	930	13	69	3.8	12.0	30	83	18.9	40.0	4.7	17.0	15.0	14.0
59	930	16	62	3.8	14.0	33	76	18.4	39.2	5.4	14.7	14.0	14.0
60	1002	18	53	3.7	15.0	27	67	20.4	57.0	4.5	19.7	13.6	12.5
61	1003	8	49	4.4	15.0	36	63	22.2	48.0	4.4	17.9	16.0	13.3
62	1003	11	53	4.1	14.0	36	67	23.4	51.7	4.1	24.4	16.3	13.9
63	1110	16	75	3.4	15.0	27	84	19.0	54.3	5.0	14.7	12.9	13.7
64	1110	17	75	3.6	13.0	23	84	18.9	56.3	4.8	14.0	12.9	13.8
65	1114	12	92	3.3	8.4	24	103	20.8	52.0	6.2	13.1	9.7	18.7
66	1114	15	91	3.3	9.1	27	103	19.9	49.6	6.0	10.7	9.6	18.7
67	1125	12	84	4.4	12.0	17	95	22.3	56.5	5.0	19.0	17.7	15.0
68	1125	13	62	4.4	16.0	22	73	18.4	55.1	4.3	12.6	14.9	15.0
69	1125	14	61	4.4	16.0	27	74	21.8	54.6	4.6	7.6	13.1	15.0
70	1125	15	71	4.2	12.5	19	83	20.7	60.8	4.9	7.5	13.1	15.0
71	1125	17	70	4.5	10.5	21	82	22.2	52.7	4.7	5.9	12.9	15.0
72	1202	18	83	3.3	17.0	29	97	19.3	55.6	5.7	23.0	14.9	15.0
73	1210	17	80	3.9	9.2	27	92	19.1	57.0	5.9	23.2	20.3	14.5
74	220	11	93	3.3	8.4	39	106	24.7	37.6	5.3	15.9	14.6	13.2
75	302	14	86	3.2	11.0	24	96	22.1	55.3	4.1	10.7	14.7	11.4
76	302	15	84	3.1	9.2	24	94	22.8	56.7	4.2	9.1	14.0	11.4
77	304	15	88	3.8	9.7	22	100	19.6	57.3	5.3	5.0	10.3	14.2
78	318	10	66	5.0	11.6	36	81	22.2	40.2	5.7	5.0	9.2	11.8
79	406	16	67	4.6	8.1	18	79	19.5	63.6	4.7	11.4	15.7	10.7
80	406	19	88	3.8	8.2	17	100	20.2	55.1	6.0	9.8	13.1	12.0

TABLE B2. COMPLETE DATA SETS FOR FILTER NO. 2

	DATE		Sludges				Cake				Filter		
LINE	80/81	HOUR	Q	SSR	PF	PL	Q	TS	TVS	TPH	VAT	VAC	RPH
81	406	20	82	4.2	7.7	16	94	20.2	56.0	6.1	15.0	15.6	12.0
82	406	21	92	3.6	7.2	17	104	18.1	62.2	6.3	14.9	15.5	12.7
83	406	23	87	3.8	8.0	17	99	18.9	57.9	6.3	15.4	15.4	12.7
84	406	24	84	3.9	8.2	17	96	20.0	57.9	5.7	12.4	15.3	12.7
85	407	1	93	3.3	7.9	18	105	19.5	56.7	5.5	9.1	13.2	12.7
86	407	2	111	3.3	7.3	15	123	17.9	60.6	5.9	17.3	14.9	12.7
87	407	3	80	4.1	8.2	17	92	20.6	57.4	5.3	10.5	13.3	12.2
88	407	4	89	3.5	8.0	18	101	20.5	57.5	4.9	7.5	12.7	12.9
89	407	5	90	2.5	10.7	25	102	19.8	54.6	3.9	8.9	14.0	12.9
90	407	6	87	3.0	10.1	22	99	20.6	51.8	3.8	9.6	14.6	12.9
91	407	7	88	3.5	8.3	18	100	19.7	58.0	5.7	8.4	13.7	12.9
92	407	8	88	2.7	10.2	23	100	20.6	53.9	4.0	8.1	13.5	12.9
93	407	9	86	2.6	11.3	25	98	21.3	54.1	3.6	8.0	13.7	12.9
94	407	10	91	3.6	8.3	17	103	21.6	59.4	5.3	7.0	12.8	12.9
95	407	11	92	3.2	8.0	19	104	21.3	60.3	4.4	6.3	12.4	12.9
96	407	12	90	2.5	11.0	24	102	23.3	56.2	3.4	8.7	14.3	12.9
97	407	15	86	2.7	11.2	24	98	19.0	59.2	4.1	13.9	15.6	12.9
98	407	17	94	3.2	9.2	22	106	19.2	60.1	4.7	9.7	13.9	12.9
99	407	18	93	3.3	9.0	19	105	19.0	58.8	5.8	9.0	13.6	12.9
100	407	19	91	3.6	9.0	20	103	20.6	55.3	5.2	7.9	13.2	12.9
101	407	20	89	3.6	9.1	21	101	20.0	55.3	4.9	6.9	12.5	12.9
102	407	21	89	3.7	9.8	22	101	19.8	58.8	4.8	6.1	11.9	12.9
103	407	22	88	3.7	8.4	18	100	20.9	59.0	4.5	6.7	12.4	12.9
104	407	24	76	3.8	12.6	18	87	16.6	60.9	3.9	20.0	10.4	10.8
105	408	1	76	3.7	13.5	22	89	21.3	59.1	5.0	7.9	12.4	12.6
106	408	2	80	3.6	12.2	22	93	20.9	60.7	4.6	5.6	11.4	12.6
107	408	3	82	3.8	12.0	20	95	20.0	60.4	4.7	5.5	10.9	12.6
108	408	4	88	3.7	11.2	19	101	19.7	58.1	5.6	5.9	11.3	12.6
109	408	5	84	4.2	10.0	18	97	21.0	62.5	5.0	9.1	13.9	12.6
110	408	6	81	4.6	10.2	17	94	20.8	60.3	4.5	7.8	13.4	12.6
111	408	7	79	4.6	10.2	17	92	20.8	60.9	4.5	5.6	11.7	12.6
112	408	8	93	4.2	9.5	16	106	19.4	63.2	5.0	7.7	13.4	12.6
113	408	10	75	4.6	10.0	18	88	22.4	56.3	6.3	11.2	12.3	10.9
114	408	11	85	4.1	10.1	18	98	23.2	56.2	5.6	11.2	14.4	9.8
115	408	13	86	4.1	10.4	18	99	18.7	60.8	5.8	22.8	17.0	9.8
116	408	14	72	3.6	13.5	24	85	21.1	53.4	5.2	6.1	11.5	9.8
117	408	16	73	4.0	12.0	22	86	20.1	56.8	4.7	8.9	8.5	10.5
118	408	17	84	4.1	10.3	18	97	20.3	62.2	4.8	6.2	10.8	11.6
119	408	18	87	4.3	10.1	17	100	20.6	62.0	4.9	5.5	10.9	12.1
120	408	19	89	4.1	10.4	17	102	20.2	62.1	4.4	5.5	10.9	12.1

TABLE B2. COMPLETE DATA SETS FOR FILTER NO. 2

	DATE		Sludges					Cake			Filter		
LINE	80/81	HOUR	Q	SSR	PF	PL	Q	TS	TVS	TPH	VAT	VAC	RPH
121	408	20	99	3.1	11.8	20	112	20.4	59.5	4.6	12.0	15.5	12.1
122	408	21	96	3.1	11.8	21	109	17.7	59.3	4.7	10.7	14.7	12.1
123	408	22	98	3.5	10.5	18	111	18.3	61.8	6.0	17.7	16.7	12.1
124	408	23	92	3.3	11.7	21	105	19.5	61.4	5.3	11.9	15.3	12.1
125	409	1	88	3.1	13.0	23	101	19.4	58.7	4.4	9.9	14.3	12.1
126	409	2	88	2.7	15.0	26	101	20.1	57.1	3.9	9.7	14.4	12.1
127	409	3	89	2.4	16.5	29	102	20.2	56.4	3.7	13.7	16.1	12.1
128	409	4	98	2.4	15.0	27	111	21.2	61.6	4.3	19.6	15.8	12.1
129	409	5	98	2.6	14.0	26	111	20.1	61.0	4.6	10.0	14.2	12.1
130	409	6	98	2.8	13.5	21	111	20.2	63.7	5.0	9.4	13.7	12.1
131	409	7	97	2.7	13.5	21	110	20.1	62.6	4.8	11.1	15.0	12.1
132	409	8	93	2.8	14.0	24	106	20.4	61.8	4.5	9.3	13.8	12.1
133	409	9	92	2.5	16.0	27	105	21.3	57.3	3.9	10.1	14.8	12.1
134	409	10	98	2.2	16.0	29	111	22.0	58.1	3.5	15.4	16.5	12.1
135	409	11	96	2.5	15.0	26	109	23.0	60.9	3.7	17.2	16.4	13.5
136	609	19	49	4.4	13.5	33	61	20.5	45.6	4.2	13.2	5.1	12.6
137	609	20	61	4.4	11.5	26	73	20.7	45.2	5.3	18.8	9.2	12.6
138	609	21	54	4.5	12.0	29	66	18.7	52.5	5.4	19.1	9.4	12.6
139	609	22	51	4.5	13.0	31	63	20.9	39.0	5.4	16.4	7.9	12.6
140	609	23	46	4.5	15.0	36	58	19.8	34.8	5.2	16.3	6.3	11.3
141	610	2	41	4.5	16.0	39	53	20.2	34.1	4.8	18.8	6.4	11.3
142	610	3	40	4.5	16.5	36	52	20.6	27.1	5.8	20.3	5.4	10.4
143	610	4	54	4.5	12.5	24	65	20.4	41.0	5.2	18.5	8.6	11.2
144	610	5	44	4.5	15.0	29	57	20.9	40.5	4.5	24.4	9.5	11.2
145	610	6	44	4.5	15.0	26	57	19.8	40.0	4.9	16.5	6.8	11.2
146	610	7	52	4.6	12.0	21	64	20.3	44.6	5.0	17.3	9.4	11.2
147	610	8	50	4.6	13.0	22	60	20.4	44.7	5.0	17.1	9.1	11.2
148	610	9	51	4.6	13.0	24	62	20.8	43.5	4.4	20.6	9.6	12.1
149	610	10	53	4.6	12.0	24	64	19.8	41.3	5.1	13.2	8.1	12.9
150	610	17	54	4.4	13.0	23	62	18.6	56.9	4.6	19.5	9.7	12.0
151	610	19	43	4.2	16.5	25	51	18.2	52.4	4.3	17.1	8.2	10.7
152	610	20	50	4.3	14.0	20	58	18.1	54.1	4.4	12.8	9.4	11.6
153	610	21	52	4.3	13.5	20	61	18.9	51.5	4.5	13.5	9.4	12.1
154	610	22	54	4.3	13.0	19	63	19.3	55.5	4.4	17.7	9.8	12.8
155	610	23	52	4.3	13.0	20	61	18.3	52.1	4.2	11.9	9.2	13.1
156	610	24	51	4.3	14.0	20	60	17.9	53.6	4.0	10.8	9.1	13.1
157	611	1	49	4.2	14.5	22	58	19.3	55.1	3.9	15.9	9.9	13.1
158	611	2	51	4.1	14.0	21	60	18.5	53.5	4.3	8.8	8.2	13.1
159	611	3	53	4.3	13.5	19	62	17.9	56.5	3.9	11.9	9.3	13.1
160	611	4	53	4.4	13.0	19	62	18.3	55.1	4.1	13.9	9.6	13.1

TABLE B2. COMPLETE DATA SETS FOR FILTER NO. 2

	DATE		Sludges					Cake			Filter		
LINE	80/81	HOUR	Q	SSR	PF	PL	Q	TS	TVS	TPH	VAT	VAC	RPH
161	611	5	48	4.4	14.0	21	57	18.8	54.5	4.2	11.9	9.4	12.3
162	611	6	50	4.4	13.5	20	59	18.6	55.5	4.0	12.2	9.5	12.2
163	611	7	50	4.4	13.5	20	59	18.1	57.3	4.0	14.4	9.8	12.2
164	611	20	52	4.3	13.0	21	61	20.9	48.8	4.8	14.9	9.9	12.7
165	611	22	52	4.3	13.5	22	61	18.4	56.7	4.1	11.0	8.8	12.6
166	611	23	49	4.3	14.0	23	58	19.0	52.7	4.2	11.2	8.0	12.2
167	611	24	48	4.4	14.0	25	57	20.5	52.1	3.9	13.9	9.0	12.2
168	612	1	47	4.3	16.5	25	56	18.5	48.8	4.0	10.7	7.1	12.2
169	612	2	47	4.3	15.0	24	56	18.7	52.2	4.1	10.0	7.5	12.2
170	612	3	51	4.3	14.0	20	60	19.5	53.9	4.1	11.5	8.1	12.2
171	612	4	50	4.3	14.0	20	59	19.1	52.4	4.1	12.7	8.9	12.2
172	612	5	51	4.4	14.0	20	60	18.4	53.6	4.3	13.3	9.3	12.2
173	612	6	48	4.3	15.0	22	57	15.9	55.9	4.0	10.8	7.5	12.2
174	612	7	52	4.3	13.5	19	61	19.5	51.3	4.2	11.2	9.2	12.2
175	624	11	57	4.2	9.8	28	69	22.0	45.8	4.9	15.9	5.0	12.2
176	624	12	63	4.1	9.1	25	75	20.9	43.3	4.6	16.6	5.5	12.6
177	624	13	67	4.1	8.4	22	79	21.2	44.1	4.7	17.3	5.5	12.6
178	624	14	67	4.1	8.2	26	80	18.7	35.5	4.9	18.1	5.5	12.6
179	624	15	67	4.1	8.2	24	79	23.3	43.5	5.2	19.6	4.3	12.6
180	624	16	67	4.1	8.3	25	79	20.9	40.1	4.8	22.2	5.1	13.3
181	624	17	67	4.2	8.4	24	80	22.0	46.3	4.9	19.4	5.3	13.5
182	624	18	67	4.1	8.3	25	80	18.5	45.6	5.5	18.2	5.0	13.8
183	624	19	67	3.9	8.9	26	80	22.0	43.9	5.4	16.9	4.9	12.4
184	624	20	67	4.0	8.2	26	80	21.3	43.8	4.6	22.2	5.0	13.3
185	624	21	67	3.9	9.2	26	80	22.1	43.5	4.5	16.1	4.8	14.2